CAEP IMPACTS AND SCIENCE GROUP (ISG)
White Papers

ICAO

ENVIRONMENT

CONTRAIL SCIENCE WORKSHOP REPORT

2025

CAEP IMPACTS AND SCIENCE GROUP (ISG)- CONTRAIL SCIENCE WORKSHOP REPORT

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SUMMARY

The Impacts and Science Group (ISG) of the International Civil Aviation Organization's (ICAO) Committee on Aviation Environmental Protection (CAEP) has an ongoing work programme to inform the triennial meetings of CAEP on the latest scientific developments as they pertain to aviation and its impacts on the environment. The ISG membership comprises experienced research scientists, nominated by Member States and Observer Organizations of CAEP. During the CAEP/13 cycle (2022-2025), the ISG had a task (I.02) as follows:

"Assessment of the contrail forcing term and the overall uncertainties, trade-offs between contrails and CO_2 (avoidance), co-benefits with lower carbon footprint fuels with lower aromatic/sulphur content."

As a part of the overall task, ISG was to:

"Conduct a workshop for ISG to obtain input from internationally recognized contrail science experts. Based on the knowledge gathered from this workshop, to develop a summary report on: a) state of knowledge of AIC [Aviation Induced Cloudiness] radiative forcing along with uncertainties; b) impact of SAF on AIC climate impacts; c) state of knowledge of contrail prediction and accuracy; and d) status of warming contrail mitigation efforts. This report will provide the state of science and the need and inform CAEP of the available pathways for mitigating persistent warming contrails."

To fulfil this task, the ISG co-rapporteurs, in conjunction with the CAEP Secretariat, organized a workshop that brought together experts in contrail science from within ISG and external to it, in

[1] Full list of participants in the Appendix

order to discuss a range of issues. The workshop was held in ICAO's headquarters, Montreal, from November 14-17, 2023.

The aim of the workshop was to address all aspects of task I.02 and synthesize the current state of knowledge pertaining to task I.02. Through extensive discussion over five sessions, each targeting a core subject area, areas of related certainty and remaining uncertainty were identified. This report summarizes the conclusions of the workshop and is organized following the five themed sessions, in which the subject matter was discussed extensively. The sessions were as follows:

1. Contrail formation and evolution: nucleation, emissions, microphysics, measurements, modelling;
2. Cloud microphysics and radiative transfer;
3. The background atmosphere: water vapour measurements and ice supersaturation, satellite observations;
4. The treatment of contrails and contrail cirrus in large-scale models, and feedbacks;
5. Aircraft emissions and cloud radiation interactions.

INTRODUCTION AND BACKGROUND

Condensation trails ('contrails') are a well-known phenomenon of the triggering of ice clouds by aircraft at cruising altitudes. Linear contrails can be formed behind aircraft under certain atmospheric conditions of temperature and humidity. If the atmosphere is supersaturated with respect to ice, contrails may persist more than a few minutes. These persistent contrails can develop into 'contrail cirrus' clouds, which may spread to form large cirrus cloud decks and last for many hours.

For some decades, the potential effect of contrail cirrus on climate warming has been discussed. The landmark Special Report of the Intergovernmental Panel on Climate Change, 'Aviation and the Global Atmosphere' (IPCC, 1999) highlighted this effect and the large uncertainties associated with it. Much progress has been made in the period since IPCC (1999) in terms of understanding the formation and nature of contrails/contrail cirrus through extensive measurements, and modelling has provided further insights into their evolution and the potential effective radiative forcing (ERF) of these clouds.

The purpose of this workshop report is to provide CAEP Members and Observers with an up-to-date group consensus on certainties and uncertainties of various aspects of the science, grouped in a series of topics.

The topics discussed in the workshop were as follows:

1. Contrail formation and evolution: emissions, nucleation, microphysics, measurements, modelling.
2. Cloud microphysics and radiative transfer.
3. The background atmosphere: water vapour measurements and ice supersaturation, satellite observations.
4. The treatment of contrails and contrail cirrus in large-scale models, and feedbacks.
5. Aircraft emissions and cloud-radiation interactions.

The document is **not** intended to be a comprehensive review or assessment of contrails. There are examples in the literature of such reviews and assessments, to which the interested reader is referred, including (amongst many others), for example, Schumann (1996); Karcher (2018); Lee et al. (2021); IPCC (2021)/Naik et al. (2021); Singh et al. (2024). Contrail science is highly complex with a dense literature base. Here, we provide peer-reviewed literature references to the material covered in the workshop discussions that allowed the participants to reach their conclusions.

CONTRAIL SCIENCE WORKSHOP SUMMARY

Session 1. Contrail formation and evolution – emissions, nucleation, microphysics, measurements, modelling

Certainties

1. There is an overall framework by which contrail formation is understood for present fuels and aircraft, such that contrail formation can be predicted by thermodynamics alone (the Schmidt-Appleman criterion). However, contrail ice crystals are formed as the result of microphysical processes such as supersaturation and nucleation from the interaction of particles and water vapour, the latter of which is not captured by the Schmidt-Appleman criterion (see e.g. Jensen et al., 1998, Kärcher et al., 2015).
2. Aircraft engines using current fossil-based kerosene emit water vapour (~1.25 kg per kg of fuel) and many aerosols, of the order ~ 1-100 nm in diameter, often consisting of a small nucleation particle size mode and a slightly larger soot particle size mode. Some of these particles can act as cloud condensation nuclei (CCN). Homogeneous nucleation can result in contrail formation under clean air conditions, but more commonly it is the homogeneous freezing of water vapour on soot particles in traditional rich burn architectures which is responsible for contrail formation (Koehler et al., 2009). Empirical evidence shows that soot particle precursors include aromatic fuel compounds and possibly naphthalenes (Liscinsky et al., 2013). Young contrail properties are influenced by the size and number concentration of the CCNs (Gorbunov et al., 2001).
3. Contrails form when supercooled water (from the engine combustion process) droplets freeze very rapidly, and the associated homogeneous ice nucleation process

is the dominant freezing mode. If the atmosphere is ice-supersaturated, ambient water vapour will continue to deposit onto the surface of the ice crystals, and they will grow. The lifetime of these persistent ice crystals will largely be dependent on local meteorology through the interaction of the degree and extent of the ambient ice-supersaturation (ISS) region, the properties of young persistent ice crystals, and their evolution through growth, gravitational settling and sublimation. Contrails that last beyond 10 minutes are referred to as 'persistent contrails' (WMO), although definitions of 'persistence' vary in the literature. The net radiative effect on climate from contrails depends on insolation, their microphysical and optical properties, persistence and spread, as well as on the local surface albedo and the vertical distribution of temperature, humidity and cloudiness (Jensen et al., 1994).

4. The radiative effects on climate from contrails depends on their persistence and spread, to a first order. Only the persistent contrails that spread to form contrail-cirrus (potentially to 100s of km²) may have a significant radiative effect (Jensen et al., 1994). The radiative forcing of short-lived contrails is far less significant due to their short lifetime (seconds-minutes) (Karcher, 2018).

5. During the day, contrails scatter solar radiation (cooling) and absorb and re-emit infrared radiation from the earth and surrounding atmosphere (warming); the net effect of these opposite effects may be a net negative or net positive forcing. During the night, they exert a positive forcing (warming) exclusively from infrared. There is consensus that the annual global average forcing is a net positive one from contrails and contrail cirrus (Lee et al., 2021).

6. In general, for the present-day fleet, and routes, the winter contrail cover is larger than in summer. In addition, longer daytime hours reduce the net contrail effect in summer, because of a larger proportion of daytime flights (Rodríguez De León et al., 2018).

Uncertainties

1. There are many uncertainties outstanding in the estimation of the global Radiative Forcing (RF), the calculation of Effective Radiative Forcing (ERF), and the climate efficacy of contrails and contrail cirrus (Lee et al., 2023).

2. There are many outstanding uncertainties in terms of how contrail formation and properties will change with changed fuel properties (e.g. sustainable aviation fuels 'SAF', which may have lower aromatic and sulphur content than prevailing fossil jet fuels) and/or engine technologies (e.g. lean burn vs rich burn engines, oil venting schemes); with newer "low soot" engine technologies being more uncertain. The impact of individual chemical components of jet fuel has started to be addressed in recent flight test campaigns. Recent measurements showing a reduction in ice crystal number with soot number for "soot-rich" engines (Voigt et al., 2021; Bräuer et al., 2021; Märkl et al., 2024). This is important since there are discussions on changing fuel composition as a contrail mitigation option.

3. There are only a few measurements of how changes in fuel and technology can influence ice crystal number (Voigt et al., 2021; Bräuer et al., 2021; Märkl et al., 2024), therefore the scientific community relies on modelling activities. Several modelling studies exist which quantify the effect of soot or ice particle reduction on the radiative forcing from contrails (Burkhardt, 2018; Bier and Burkhardt; 2023; Teoh et al., 2022; Teoh et al., 2024; Märkl et al., 2024). The evaluation of the radiative forcing from contrails through independent satellite analysis is difficult. Also, more in-flight observations are required to investigate the different dependencies on fuel and engine properties as well as ambient conditions.

4. Satellite, airborne (Borella et al., 2024) and ground observations can show where some ISS regions occur but with limited spatial and temporal accuracy and resolution (Lamquin et al., 2012, Gierens et al., 2004).

5. More experimental data are required on the impact of fuel and technology on contrail ice crystal formation, as measured ‘in-flight’ (e.g. Kleine et al., 2018; Voigt et al., 2021; Märkl et al., 2024). Ground-based tests at airport facilities pose a limitation on the measurement time scales and dynamics experienced during flight.

6. There are only two published global models (Chen and Gettelman, 2013; Bier and Burkhardt, 2022) currently being used that have a fully coupled water-vapour budget. This small number of available models is an unsatisfactory situation and results in a very low level of confidence in the results, since assessments of ERF would ideally be based on more models, in order to reach a consensus. It is noted, however, that there are other developments underway.

7. Models are quite sensitive to input assumptions, and some of these assumptions/approximations are known to be incomplete (e.g. the treatment of the importance of volatile particles under lean burn/SAF fuel conditions at approximately $< 10^{14}$ soot particles/kg fuel) (Yu et al., 2024). On the positive side, the models do provide uncertainty estimates relative to their input assumptions.

8. Models are also sensitive to the representation of ISS. Occurrence of ISS at the larger scale is less problematic but the relevant smaller spatial scales are not currently well predicted.

Session 2. Cloud microphysics and radiative transfer

Certainties

1. Contrails will persist and evolve into cirrus-like clouds under ice-supersaturated atmospheric conditions (Schumann, 2012). Understanding the spatial (horizontal and vertical) and temporal scales of ice supersaturated regions (ISSRs), when, and where, contrails will persist (Gierens and Spichtinger, 2000), is essential to determining their impact on the climate and possible mitigation.

2. Aircraft engines emit some gases and non-volatile particles (nvPM) that can act as cloud condensation nuclei. Their role in the cloud microphysical process is particularly

complex. There are some studies of nvPM produced in the combustion "soot-rich" regime of current technology engines at cruise, which show that a reduction in nvPM has a potential beneficial impact on reducing contrail-cirrus RF (Zhang, et al., 2022). Engine technologies with significantly reduced nvPM emissions need further study, since volatile particle formation may become dominant in ice crystal formation.

3. Fuel composition and fuel type can impact contrail microphysics (Durdina et al. 2024), e.g. hydrogen-powered aircraft that produce more water vapour but no sulphur and nvPM). There could be some benefits from SAF use (due to changes in aviation fuel composition) in the reduction of particles; however, lean burn technology reduces soot number concentrations by orders of magnitude, rather than tens of percent. Current limited availability of SAFs and current restrictions on the percentage fraction allowed mean the potential benefits will take time to penetrate the market. The same fuel composition benefits to particles and other emissions may be obtained by changing the composition of fossil-derived aviation fuel in the refining process, with corresponding increased refinery energy demands.

4. The RF of an individual contrail in an otherwise cloud free atmosphere depends on the optical depth to the first order (Kärcher et al. 2009). The optical depth depends on the Ice Water Concentration (IWC) and ice crystal number concentration (De Leon et al. 2012).

Uncertainties

1. The formation and evolution of ice crystals in aircraft contrails and induced cirrus clouds is complex. Ice particle size distribution impacts the optical properties and lifetime of a contrail (Bock et al. 2016).

2. The role of ambient particles is likely to be important to the formation of contrail ice crystals (and hence the contrail ice particle size distribution), particularly for low-particulate engines and fuels (Yu et al. 2024).

3. The formation of contrails within natural cirrus is poorly understood (Verma and Burkhardt, 2022). Natural clouds overlapping with contrails complicates estimating the net radiative effect of a contrail. Current global estimates parameterize this effect. An improved characterization is needed in models, how they treat radiation and the interaction with clouds. However, there is a more general problem of representing clouds in climate models, which represents a significant uncertainty (Regayre et al. 2014).

4. Climate models designed to predict ISSRs can capture the overall statistics of observed ice supersaturation (Gettelman et al 2010). However, current forecast and reanalysis systems are not designed to predict the fine-scale structure in space and time of ISSRs necessary for flight-by-flight avoidance (Gierens et al 2020).

5. There is limited knowledge on the nature of embedded contrails within cirrus clouds and the radiative impact (Immler et al. 2008, Lohmann et al., 2008).

6. There are still uncertainties concerning the evolution of contrails into cirrus clouds (Singh et al., 2024). A better understanding of cirrus lifetime and optical depth is needed, as well as of the evolution of ice crystal habits.

Session 3. The background atmosphere – water vapour measurements and ice supersaturation, satellite observations

Certainties

1. ISS and ISSRs are crucial to contrail persistence.

2. In terms of the occurrence, scales and frequencies of ISSRs, the following is understood:

   – Based on persistent contrails and contrail-cirrus observations, there are some estimates on the spatio-temporal ISSR frequency, on average, based on in situ measurements (e.g. Borella et al., 2024). However, representative coverage is poor, and satellite measurements, which have insufficient vertical resolution (Gierens et al., 2020; Agarwal et al., 2022; Lee et al., 2023).

   – The maximum frequency of the ISS occurrence is close to the tropopause and up to 150% Relative Humidity with respect to ice (RHi) (Spichtinger et al., 2004; Kramer et al., 2020).

   – Most RHi values around the tropopause occur below and around ice supersaturation (90-120%) (Fusina et al., 2007).

   – The occurrence of ISS is not binary (i.e. at 100%), RHi may fluctuate around saturation due to small-scale temperature fluctuations in regions where contrail ice numbers are sufficiently large, as sublimation is not immediate (Immler et al., 2008).

   – Regarding the impact of higher ISS on persistent contrail formation, at 130% RHi it is likely that natural cirrus would have formed if no contrail had formed (Krämer et al., 2009). The presence of sufficiently thick cirrus clouds may constrain mean RHi to ice saturation (Krämer et al., 2009). Small-scale dynamical variability may drive the air away from such a state (Kärcher et al., 2023):

   – The location of ISSRs is on average between the tropopause and 4 km below but does not often occur above the tropopause (Petzold et al., 2020). Seasonality and regionality of the tropopause is important to contrail formation and ISS altitudes will vary by latitude (Irvine et al., 2012).

   – Based on persistent contrail observations in some world areas, the average spatial scale of ISSRs is estimated to be of 150 km in the horizontal (Spichtinger et al., 2016) and 1 km in the vertical. ISSRs are typically heterogeneous.

– Climate change will impact ISS occurrence (Irvine et al., 2015). However, the formation mechanisms for ISSRs will not change. The changing climate will be unlikely to change the average ISSR, however there could be local changes observed, e.g. as aerosol concentrations change, ISS may also change.

3. Regarding instruments to identify ISSRs:

– Atmospheric observations are critical to understanding ISSRs from a climatological perspective (Krämer et al., 2009). The availability of a greater number of observations will lead to a better basis for model/data comparison. However, there are known problems with water vapour transport and temperature biases that prevent us from better simulating even the large-scale occurrence of ISSRs. Also, for the contrail problem, we need high resolution data on ice supersaturation, both spatially and temporally.

– ISSRs cannot be directly observed but their presence can be evaluated from the measurement of weather parameters like temperature, pressure, and specific humidity (Horeau et al., 2016).

– Observations of the vertical and horizontal structure of the atmosphere are important, with the vertical structure being the most important to further understand. The spatial scale of vertical variations is much smaller than horizontal variations in the upper troposphere. However, measurements and predictions of vertical wind fields remain a constraint.

– Some in-situ aircraft-borne humidity and temperature instruments are precise and accurate enough to understand ISS, but they are research grade in-situ sensors with limited sampling (Gierens et al., 2012, Kaufmann et al., 2018). Satellite observations of humidity and temperature do not have sufficient vertical resolution to accurately assess ISSRs, but can provide large-scale climatologies (Tompkins et al., 2007).

– It is possible to measure humidity, particularly with research-grade instruments. While new technologies are under development, the requirements are important (e.g. 20 ppmv measurement capability for specific humidity at aircraft flight levels, fast sampling rate). The development of commercially available and autonomous instruments is getting (and should get) a lot of attention from a research perspective (Konjari et al., 2024).

Uncertainties

1. Routine or forecast modelling of water vapour in the upper troposphere and lower stratosphere has uncertainties due to ice nucleation processes and a dearth of routine observations. New observations from satellite, ground and in-situ (e.g. Konjari et al., 2024, Walbröl et al., 2024), are needed to improve the modelling, as well as dedicated model improvements for forecast systems (Sperber et al., 2023).

2. There is a need to accurately measure weather parameters related to ISSRs (temperature and humidity, possibly the presence of condensed ice crystals, e.g.

Kärcher et al., 2023a), as it helps interpreting other observations and will help with an accurate modelling of ISSRs (e.g. Comstock et al 2008).

3. To predict ISSRs, in-situ and near real time measurements of water vapour concentrations, and vertical winds and associated temperature fluctuations are necessary (i.e. giving measurements where and when the aircraft fly) to assimilate into forecast models. Thus, a large set of commercial aircraft fleet-wide observations would be useful (and probably necessary for forecasting ISSRs) (WMO, 2023), as is done now with aircraft temperature and wind measurements. The cost of development, certification and rolling out aircraft-borne instruments is significant, but widely distributed and the mechanism to go from aircraft to forecast model already exists (for temperature and wind, ACARS) (WMO, 2021). Efforts to compile necessary criteria and estimates of costs of implementation have been made (IATA, 2024)

4. There is utility in a larger set of humidity measurements across a wider range of stakeholders, noting that instrument sensitivities and requirements (by stakeholder) are different (WMO, 2023). By way of example, there are different water vapour measurement requirements to understand the atmospheric cloudiness and for aircraft icing. For ISSRs and persistent contrails, the needed benchmark of observations at flight altitude at the minimum temperature encountered by aircraft of the atmospheric specific humidity is 20 ppmv.

5. A better understanding of the natural clouds in the atmosphere is needed to improve the assimilation process of data (e.g. Kärcher et al., 2022).

6. Regarding the modelling of ISSRs:

   - There is currently no ability to provide a daily accurate forecast/nowcast of ISSRs for individual flights, mostly due to inadequate representation of ISSRs in many weather forecast systems and the lack of humidity data in aircraft flight lanes.
   - Large scale predictions of ISS are generally good but inadequate for potential contrail avoidance operational procedures, since the smaller scale variability required for individual flights is not predicted with sufficient accuracy (Gierens et al., 2020; Hofer et al., 2024).
   - Very little information is known on how vertical model profiles interact with contrail formation schemes (Tompkins et al., 2000), due to the typical 100-500m discretization of models.
   - Ice water path is thought to be underestimated in the large-scale models (Lohmann et al., 2008), despite large uncertainties linked to their measurement.
   - Observation campaigns have shown that the more general spatial and temporal forecasts of ISSRs can be broadly successful (e.g. Voigt et al., 2010), noting that these campaign days and location are aimed at days when ISSRs will exist, and research aircraft have instrumentation to find them.

– Wind shear in the atmosphere has a large uncertainty and is not well-represented in the data and low-resolution modelling. This gives some uncertainty in the prediction of the evolution/lifetime/impact of the contrail in such an air mass.

7. Consideration should be given to simulate contrails (by incorporation of appropriate microphysics) in modern storm resolving models (Stevens et al., 2020) (resolution lower than 5 km). Those models exhibit a significantly improved upper troposphere water budget, and processes governing the contrail life cycle and interactions between natural clouds and contrails may be simulated much more realistically. A lot may be learned from following such an approach even if such simulations are computationally intensive.

8. Consideration should be given to further data-driven methods, for example machine learning, to explore the formation and the evolution of persistent contrails. Examples include automated contrail detection of satellite imagery for data assimilation (Riggi-Carrolo et al., 2023). New advances in artificial intelligence will be likely important.

Session 4. The treatment of contrails and contrail cirrus in large-scale models and feedback

Certainties

1. It is important that we define what is meant by ‘models’; there are two types in current use. A small number (2) of Global Climate Models (GCM) that have a representation of contrails as ‘extra clouds’ by using many assumptions and simplifications but do have closed (mass conservative) water vapour budgets (e.g. Bock and Burkhardt, 2016; Chen and Gettelman, 2013). These can be run to determine ERF (fast feedbacks) in ‘GCM mode’, and potentially, efficacy (with long/magnified integrations, coupled with an ocean model) (e.g. Bickel et al., 2020; Ponater et al., 2021). Other models such as CoCiP (Schumann, 2012) or other plume models (Fritz et al., 2020) attempt to better represent formation and instantaneous forcing along the lifetime of individual contrails, but such plume models do not interact with the driving numerical weather prediction model (providing input data) and, therefore, cannot close the water budget, assuming instead an unconstrained source of water when forming contrails and/or depositing water on the contrail ice crystals (unless implemented inside a GCM framework) and therefore cannot calculate ERFs. Moreover, such models represent contrail microphysics in a highly simplified manner.

2. Global modelling of contrail ERF has made large advances in the last 10-15 years, mainly from two research groups, one in Europe, one in the US.

3. There are currently only two fully coupled (with water mass and energy) models available and in use that can represent a global ERF calculation. This is recognized to be a poor situation, leading to a low confidence in the results and large uncertainties. Like any model, these models could be developed further, and additional ones developed within GCM frameworks.

4. In terms of global climate modelling, many measurements/observations over the last two decades have resulted in a better representation of contrails.

5. Other models in use in the representation/analysis of contrails are 'weather models' in terms of providing inputs to plume models. Meteorological models exist at global and regional scales. There is usually a limited representation of ice-supersaturated regions (ISSRs). In terms of general statistics, for advanced nudged data assimilation models (such as ECMWF) there is a good representation of ISSRs but not their precise locations, extent and structure, in time and space (Gierens et al., 2020). We know that rapid time response in-situ measurements show a small-scale (on the spatial scale of contrails) heterogeneity within ISSRs (larger scale).

6. A lack of the ability to observe very large concentration gradients of water vapour and to simulate small-scale dynamical and microphysical processes leading to an adequate representation of the detail of ISSRs means that increased spatial resolution of models will not necessarily resolve the problem of x, y, z, t coordinate modelling on a flight-by-flight basis.

7. We lack high-quality data for temperature and humidity at relevant altitudes and geographical positions – this situation could be improved. There is agreement that there is a need for better and more frequent observational information (WMO, 2023). However, instrumentation with sufficient accuracy, precision, and reliability needs to be developed at economic cost for widespread usage and deployment. There are significant barriers to overcome, including certification and installation of the measurement and data transmission system on-board different aircraft.

Uncertainties

1. Issues should be separated more clearly. There is a need for improved understanding of present and future contrail formation and properties (under, for example, changed fuel/combustion conditions), and their representation in larger scale models to determine the size of the effects. Currently, the potential role of volatile particles is not represented. Modelling contrails for mitigation purposes (e.g., avoidance, fuel, type and/or composition changes), is a different 'problem' than determining the net effect, but by no means independent. 'Mitigation modelling' requires more verified and repeatable data that represents the mitigation approach comprehensively. So, for example, volatile PM emissions and consequential ice crystal formation and their radiative forcing is not currently represented in global models.

2. The representation of contrails within GCMs (and even plume models) remains uncertain (Lee et al. 2016). In addition, the modelling of clouds within climate models represents a major uncertainty in its own right.

3. The absolute global ERF of contrails is not well constrained (two models able to calculate it, large uncertainties, known and possible missing processes). The ERF is thought to be positive, and the central estimates (with large uncertainties) are comparable to the ERF of aviation CO_2. The factors behind the ERF response are not easy to diagnose, and the ERF adjustments are model-dependent (even to model configuration) and may vary significantly, making the size of the global ERF difficult to constrain (Regayre, 2018).

4. Contrail efficacy, and contrail ERF fast feedbacks, remain poorly understood (Ponater et al., 2021) but the available research indicates numbers below 1.

5. There is a general need to be able to model plume microphysics, diffusion, turbulence, dilution, interaction with the background atmosphere, spreading etc. and verify such modelling with observations both to understand the size of the overall effect, and for predictive purposes for mitigation, representing important processes and variables that may change (particles, soot size, soot prevalence, volatile particles, influence on ice crystal size and habit, optical properties etc.)

6. Reliable and verifiable prediction of the impact of a single contrail is currently not possible. Representing contrails statistically at the system level (through global models and forecast models) is more tractable (very different set of uncertainties). At present, it is difficult to envisage a time at which we can verifiably forecast the forcing on an individual flight basis.

7. There is uncertainty in observational verification (e.g. satellite images of optically thin old contrails) (Driver et al., 2024) that needs much more work.

Session 5. Aircraft emissions and cloud-radiation interactions

Certainties

1. Two main effects on natural clouds are considered to arise from aircraft emissions of particles in the atmosphere. The first is from soot, from sublimated contrail ice crystals which may affect the optical properties of pre-existing cirrus clouds and their formation (soot aerosol cloud interaction); the second is from sulphate particles which may affect lower-level water droplet clouds (sulphur aerosol cloud interaction) (Lee et al., 2021).

Soot aerosol cloud interaction.

2. Laboratory experiments show that aviation soot particles have a low nucleating ability at mixed phase cloud temperatures but their ice nucleation activity can be enhanced at cirrus cloud temperatures (Mahrt et al., 2018). This ice activity may be enhanced if soot is processed through contrail ice crystals that then sublimate (Mahrt

et al., 2020) although modelling work suggests that this is still of limited effectiveness in terms of affecting natural cirrus (Kärcher et al., 2021) [2].

3. There is competition in the atmosphere between homogeneous and heterogeneous freezing. Homogeneous freezing is usually with sulfuric acid solution droplets. Heterogeneous freezing can be on biological particles, soot or mineral dust at lower ISS. The presence of ice nucleating particles (INPs) can optically thicken ice clouds by enabling crystals to form on their surfaces (heterogeneous nucleation), among cirrus that initially form through the freezing of liquid aerosol at high saturations (homogeneous freezing/nucleation), the impact of INPs tends to be the opposite (Sullivan et al., 2016; Zhao et al., 2018). McGraw et al., (2020) found that the addition of aircraft soot emissions affected cirrus primarily at Northern Hemisphere latitudes where heterogeneous nucleation already dominates, causing this INP source to primarily enhance cirrus SW and LW effects with a net negative effect. McGraw et al. (2020) also noted the parameterization of the assumed efficiency of the INPs was critical. Measurements of aviation soot INP efficiency suggest that the outcome of this competition is still under discussion (Kärcher et al., 2023).

4. It is suggested that soot particles forming ice crystals at a lower ISS would result in fewer ice crystals being formed sooner and deplete the available water in the local atmosphere, resulting in a negative forcing. This result has been shown in models but relies on unproven assumptions above.

Sulphur aerosol cloud interaction

5. Oxidised sulphur compounds are emitted from the engine exhaust at rates dependent on the fuel composition, approximately 98% of it in the form SO_2 (Jurkatt et al., 2011), while the rest directly as sulphate aerosol. Sulphur dioxide is oxidised in the atmosphere to aerosol particles over the timescale of hours to days. If the sulphate aerosol descends to levels where liquid clouds form, established theory and observations show that more numerous, smaller water droplets can be formed (over the counterfactual of no sulphate aerosol being present), resulting in optically brighter clouds, that reflect solar radiation back to space with a cooling effect (Twomey, 1974, 1977). This cannot be observed for aviation, only modelled.

6. The forcing from this effect is almost certain to be negative but the magnitude is highly uncertain. It has been simulated as of similar magnitude and opposite sign (negative) to contrail cirrus positive ERF.

Uncertainties

1. Both soot and sulphur aerosol cloud interactions can only be modelled. There are very few global models that can treat this effect and the range of results is in very poor agreement (see Figure 5 of Lee et al., 2021). There are other useful model

[2] A recently published laboratory study, designed to test the potential of contrail processed soot as ice-nuclei, further calls into question the potential importance of contrail processed soot as heterogeneous ice nuclei (Testa et al., 2024)

approaches, including cirrus cloud column models, that can be used for studying the effect (Kärcher et al., 2021; Kärcher, 2022).

2. The background mineral aerosol affects the soot aerosol cloud interaction, diminishing the role of contrail-processed aviation soot (Kärcher et al., 2023), and so represents a significant uncertainty (abundance now, and in the future) (e.g. Hoose and Möhler, 2012).

3. The degree to which reduced aerosol particle emissions from SAF or lean-burn combustion engines will affect both sulphur and soot aerosol cloud interactions is not known, although complete removal of sulphur from fuel will inevitably remove the negative forcing. The 'response function' to lower sulphur levels is unknown. SAF and lean burn engines have been shown to reduce soot aerosol numbers (Moore et al., 2017; Kelesidis et al., 2023).

4. The competition between aviation soot and other particles and their interaction/effect on cirrus is very hard to study in observations, and therefore modelling is performed. Some model results indicate a strong negative forcing (e.g. Penner et al., 2018). However, the results of different studies tend to depend on how ice formation from aviation soot is parameterized at ice supersaturations lower than that needed for homogeneous freezing. Studies that prescribe high ice supersaturation thresholds for soot to become activated to ice result in small soot RF values (e.g. Gettelman & Chen, 2013; Pitari et al., 2015; Righi et al., 2021). An aviation-soot cirrus simulation of processes suggests that dynamical processes (updraft velocities) and the size, number and nature of both aviation and background aerosols are critical determinants of the effect of aircraft soot on pre-existing cirrus clouds (Kärcher et al., 2023).

5. If the net effect of soot and sulphur emissions is considered, then the aerosol cloud interaction effect (soot and ice clouds, sulphur and liquid clouds) could potentially offset or even completely counterbalance the net warming effect of contrails (Lee et al., 2023), but most simulations point at low indirect cloud impacts from soot.

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LIST OF ABBREVIATIONS

ACARS	Aircraft Communications Addressing and Reporting System
AIC	Aviation Induced Cloudiness
CAEP	Committee on Aviation Environmental Protection
CCN	Cloud Condensation Nuclei
CoCiP	Contrail Cirrus Prediction (model)
CONTRAILS	Condensation Trails
ECMWF	European Centre for Medium-Range Weather Forecast
ERF	Effective Radiative Forcing
GCM	Global Climate Models
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
INP	Ice Nucleating Particles
IPCC	Intergovernmental Panel on Climate Change
ISG	Impacts and Science Group
ISS	Ice Supersaturation
ISSR	Ice Supersaturated Region
IWC	Ice Water Concentration
nvPM	non-volatile particles
RF	Radiative Forcing
RHi	Relative Humidity with respect to ice
SAF	Sustainable Aviation Fuels
WMO	World Meteorological Organization

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APPENDIX. CAEP ISG Contrail Science Workshop Participants

LAST NAME	FIRST NAME	STATE/ORGANIZATION
Barrett	Steven	UNITED STATES
Lee	David	UNITED KINGDOM
Bonne	Nicolas	FRANCE
Block	Alejandro	IATA
Johansson	Daniel	SWEDEN
Wuebbles	Donald	UNITED STATES
Miake-Lye	Richard	UNITED STATES
Arunachalam	Saravanan	UNITED STATES
Manneville	Alexis	ICCAIA
Miller	Cassandra	ICCAIA
Swann	Peter	ICCAIA
Kagaya	Ryo	ICCAIA
Baughcum	Steve	ICCAIA
McDonald	Ted	CANADA
Brons	Robert	IFALPA
Boehm	Asuka	CANSO
Garcia Claro	Miguel	IBAC
Gettelman	Andrew	UNITED STATES
Voigt	Christiane	GERMANY
Delhaye	David	FRANCE
Burkhardt	Ulrike	GERMANY
Yin	Feijia	NETHERLANDS
Stettler	Marc	UNITED KINGDOM
Moore	Richard	UNITED STATES
Rodriguez De Leon	Ruben	UNITED KINGDOM
Eastham	Sebastian	UNITED STATES
Kärcher	Bernd	GERMANY (external expert)
Wells	Nicole	UNITED STATES
Owen	Bethan	UNITED KINGDOM
van Velthoven	Peter	NETHERLANDS
Kim	Brian	ICCAIA
Mannville	Alexis	ICCAIA
Rollins	Andrew	UNITED STATES
Stromatas	Stavros	EU
Marizy	Corinne	ICCAIA
Goobie	Scott	IBAC
Catalano	Fernando	BRAZIL

Carter	William	UNITED STATES (external expert)
Kanji	Zamin	SWITZERLAND
Ngo	Derek	UNITED STATES (external expert)
Mwangi	Francis	KENYA
Altuntas	Önder	TURKEY
Dickson	Neil	ICAO
Medvedev	Yury	ICAO