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CLIMATE ACTION: ADDRESSING CONTRAILS

WAYPOINT 2050

Aviation has a strong track record of solving difficult global challenges.

Most recently, in a collective effort to deal with its climate change impact, the industry adopted a goal of net zero carbon emissions by 2050. This was also taken up by the world's governments at the International Civil Aviation Organization (ICAO) which adopted a similar goal at its 41st Assembly in 2022[1]. Removing carbon dioxide (CO_2) emissions from aircraft operations will require new energy sources and technological developments as well as efficiency improvements to reduce fuel use. Whilst this remains a significant challenge, the problem is well understood and the solutions are in progress: with the right policy, drive and determination, plans are in place for the decarbonisation of civil aviation.

The aviation industry is also focused on another of its climate impacts which has less clarity or mature solutions: the causes and consequences of other aviation emissions besides CO_2, and their atmospheric effects. Among those non-CO_2 impacts, condensation trails, or 'contrails', (the familiar white lines in the sky that are, in essence, human-made clouds) could have the most significant warming effect.

This paper will focus on the state of science for contrail climate impact and the need for continued research (including operational trials) in several areas before viable mitigation approaches are brought into daily operation across the aviation system.

Aviation has a firm commitment to reduce its climate impact. It has a robust plan in place for the significant challenge of net-zero CO_2 emissions by 2050. At the same time, the sector is stepping up efforts to address the non-CO_2 impacts from aviation, most prominently the formation of some types of contrails. Despite some complexities in several aspects of the underlying science, the sector is engaged across a range of research and operational initiatives to identify how best to avoid warming contrails as part of a wider climate impact mitigation effort. Large-scale trails – both modelled and in real-world operations – are strongly supported to identify how these mitigation efforts could eventually play a role in daily flight operations.

Contrails have an overall warming impact

Scientific consensus shows that persistent warming contrails have a climate impact.

There is still uncertainty over some key implementation aspects

i. Where contrails will be formed and persist (ISSR locations[2]).

ii. What the climate impact of individual contrails is, and how this could balance with the climate impact of extra CO_2 due to route changes.

iii. Understanding which engine types drive contrail properties.

iv. How to link any mitigation measures to individual flights, or whether this is even desirable.

We are already working on ways to avoid contrail formation

Many trials and research projects are underway aiming to provide operational and technological solutions to persistent, warming contrail formation. These should continue and be coordinated to ensure the most efficient outcomes.

The challenge of contrails

In addition to CO_2 emissions, aviation (like many other sectors) is responsible for other "non-CO_2 effects" that can have an impact on the climate. These result from complex interactions between aircraft emissions and the atmosphere. They include mainly soot particles, nitrogen oxides (NOx) and sulphur oxides (SOx). Soot particles are due to the composition of (carbon-based) aviation fuel and combustion technology; NOx emissions are caused by combustion at high temperatures; and SOx are due to the sulphur content of the fuel. The industry has been committed for years to advancing innovative combustion technologies to reduce soot particulates and NOx emissions, which also have a proven impact on the climate[3].

Water vapour is also emitted as a byproduct of fuel combustion and this can form condensation trails, which are made of ice crystals and commonly referred to as 'contrails'. Contrails are formed during flight if the ambient conditions and water vapour in the atmosphere are favourable for the condensation of water vapour from the engine exhaust. When small carbon particles are released from the aircraft's exhaust, water vapour can condense onto these particles and naturally-present aerosols will form high-altitude ice clouds. Some of these clouds only last for a few seconds, but if the air is humid and cold enough, they can persist for hours and spread across large sections of airspace.

Multiple efforts are underway to identify ways of avoiding the formation of impactful persistent contrails, through alternative fuels, revolutionary combustion technology and particularly operational improvements.

What we know and don't know

Some contrails (particularly those occurring during the day) have a cooling effect by reducing the solar radiation reaching the Earth's surface, much like naturally occurring clouds. Some (particularly those occurring at night) have a warming effect by trapping heat in the atmosphere, rather than allowing it to escape. The latest scientific consensus is that contrails have, on balance, a warming impact, with a radiative effect potentially in the same order of magnitude as aviation's CO_2 emissions. Although the quantification of this impact currently has low confidence levels and more research is needed to fully understand the overall climate impact, mitigation options are already being trialled and tested.

The effects of a contrail depend firstly on how it is formed (ice crystal formation varies according to the local temperature and humidity, aircraft engine and fuel composition), and secondly on how the contrail will evolve over its life (evolution of atmospheric conditions, winds shifting its position, the size of the ice crystals and quantity). The effect and existence of a contrail depends also on its geographical position, as well as the season and time. Current scientific understanding is that, on balance, contrails are warming and we should work to try and avoid the formation of persistent contrails that produce a warming effect. There are indications that around 10% of the flights that produce contrails (so ~2-3% of all flights worldwide) account for around 80% of the warming that is generated by contrails[4].

Not all contrails are warming. Some only last a few minutes before dissipating, others are cooling, or balance the cooling and warming effects, and a small proportion of all contrails formed have a high warming effect. Established scientific consensus suggests that, on balance, there is more of a warming impact when all contrails are considered.

The aviation industry is committed to mitigating its impact on the climate and is actively contributing to scientific research, as well as undertaking operational trials and other studies aimed at developing the means to reliably reduce persistent warming contrails through a variety of mitigation options, further reducing the climate impacts of the sector. Studies to date have shown high degrees of false positives (in which a persistent contrail was forecast to form but did not) and false negatives (in which a persistent contrail was not anticipated to form and yet did). This makes establishing effective operational mitigation methods and estimating the impacts very challenging.

A number of solutions are being tested mainly focusing on re-routing flights in order to avoid the “ice super-saturated regions” (ISSRs) of the atmosphere, where persistent (potentially warming) contrails tend to form. Whilst weather forecasts can help to locate where these regions may form, it is currently very difficult to identify them in real-time and forecast where they might occur in the near-term. A certain degree of precision is critical to enable the industry to build route deviations into flight operations as a mitigation option. Another challenge is accurately estimating the warming or cooling effect of an individual contrail inside a given region. This is particularly important to ensure the overall climate benefit of the re-routing, if the aircraft deviation would result in extra fuel burn and associated CO_2 emissions.

A strong collaborative effort is underway across industry and the research community to provide greater clarity on the solutions to these challenges and better quantification of the climate impacts.

Whilst research continues to advance understanding of the non-CO_2 aspects of aviation (where there is lower certainty), the priority for industry and governments with regards to climate action should continue to be CO_2 emissions reduction (where there is high certainty) and the significant efforts underway to reach net-zero carbon by 2050.

State of the science: questions to resolve

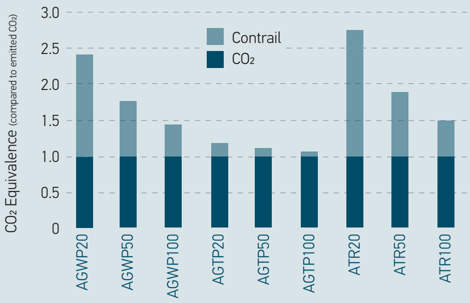
Scientific uncertainty regarding contrails is primarily related to four aspects:

i. **Prediction and identification of contrail-prone regions.** The exact location of where contrails will form, known as ice super-saturated regions (ISSRs), are often very concentrated localised zones of a few hundred kilometres in horizontal length (100-200 kilometres on average) and a few hundred meters in thickness, although they can also be much more significant in size. As with other atmospheric conditions, they shift position as ambient weather changes and are affected by the winds. There is uncertainty about how to accurately forecast the presence of ISSRs (both geographically, and in altitude and time) in a way that will allow for both pre-flight planning changes as well as in-flight tactical route changes to avoid persistent contrail formation. The current low spatial and temporal granularity of temperature and humidity observation data is a hindrance to improved forecasting in such a way to be able to reliably operationalise the solutions. Humidity data can be collected from ground stations (rapid, but altitude-limited), weather balloons (infrequent), satellite observations (although these do not provide very granular altitude-specific information), and on-aircraft sensors (see discussion below). In addition, satellite imagery, as well as ground and aircraft observations can be used to detect where contrails are already being formed and whilst this may aid weather modelling, often these observations are in real-time or after the event, and so can only be used for tactical deviations or to retrospectively identify where contrails were formed. More humidity observations are required, with data fed into numerical weather prediction models to increase the accuracy of forecasts. Studies have shown that in-situ measurements correlate poorly with numerical models for humidity in the upper troposphere and lower stratosphere.

ii. **Metrics to allow an assessment of long-term climate impact vs short-term contrail impact.** Whilst the long-term climate impact of CO_2 is well-understood, the overall impact of contrails is very short-lived (in the order of minutes and hours), so the total effect on the climate is different depending on the duration assessed. The most commonly-cited metrics: Global Warming Potential (GWP), Average Temperature Response (ATR), or Global Temperature Potential (GTP) can be expressed in different time intervals (often 20, 50 or 100 years) with each providing a different assessment of the impact of emissions of CO_2 and non-CO_2 over that period. For example, the climate impact of contrails could range from 2.3 times to less than a tenth of the impact of CO_2 depending on the time frame and metric of measure chosen.

Cumulated climate impact (relative to CO_2)

The chart below illustrates the wide range of results, depending on the global warming metric chosen. This would become even more important if applying this to determine mitigation options for individual flights.



These graphs all show the same CO_2 and contrails for the same range across the North Atlantic in 2019.

However, the metric chosen can present a vastly different result. This could present a challenge when an airline needs to decided on the trade-off between extra fuel burn needed to avoid a contrail zone and the global warming advantage of doing so.

Source: Climaviation presentation to ECAC Environment Forum, May 2024

These metrics have not been developed specifically for aviation and therefore may not adequately consider the effects of non-CO_2 emissions released at altitude, but they are the most common ones used in the wider climate policy landscape (with GWP100 being the standard for the United Nations Framework Convention on Climate Change (UNFCCC)). The challenge in determining whether to mitigate a contrail comes from trying to assess what the trade-off is between the avoided warming of a reduction in contrails, compared to the warming created by the additional CO_2 from the action of diverting a flight. There is ongoing uncertainty as to how to balance the shorter-term warming effect of contrail formation vs the longer-term warming effect of extra CO_2 (and other non-CO_2) emissions from re-routing. The short lifetime of contrails compared to CO_2 makes them an appealing target with immediate benefits to limit climate warming from aviation, however balancing reductions in climate warming from contrail avoidance with increases from additional CO_2 emitted for flight diversions requires clarity on the metric for comparison. A recent paper[5] suggests it may be too early to act on current knowledge and urges more work to better understand these trade-offs.

The aviation industry will continue to work on the potential solutions which will help us avoid contrail formation and help the research community get clarity on these remaining fundamental questions.

iii. **Accounting for engine technology and fuel variability in determining contrail properties and persistence.** Variability in the performance of the different engine types, emissions, and fuel composition in use across the industry will affect the precise exhaust characteristics and any resulting contrails. Contrail radiative forcing and lifetime will change meaningfully from these characteristics, but the exact impact is poorly understood.

iv. **Identifying individual flight actions and 'attribution' of a contrail and its associated warming (or cooling).** After scientific maturity is achieved on predicting the location of ISSRs where contrails form and what climate impact they have, there must be an understanding of what would have happened if that area was not avoided. Often, policy measures attempt to incentivise change on an individual flight basis, but this may not be appropriate for contrails. For example, the climate impact of re-routing one single flight away from an ISSR, while allowing many other flights to go through it, will be negligible or zero. If all flights were diverted away from that region, what will happen to it later? Will a (naturally-occurring) cirrus cloud nevertheless form further downstream? Furthermore, what is the water vapour budget in those regions: every time an aircraft flies through an ISSR and produces a contrail, the ISSR will "dry" as the water vapour content condenses into a cirrus cloud. It is impossible to know today how many contrails will be formed inside one specific ISSR, and at what point the mass of air is "dry" enough so that it is no longer necessary to deviate flights around it.

All these uncertainties are strongly linked: the capacity to solve the problems identified in i) and the decisions to take as discussed in ii) and iii) will affect the results of iv) and probably will define if and how contrail avoidance measures should be applied.

State of science: trade-offs and complexities

In order to avoid ISSRs, aircraft can be re-routed around, above or below those regions. These changes in flight routing can increase fuel use and therefore CO_2 emissions. While the extra fuel burn needed to mitigate contrail formation has been "small" (around 2%) in some trials, it is important to appreciate that single flight experiments are not representative of real-life conditions, or the mitigation of contrail impacts at scale. The climate benefit of deviating a single flight to avoid an ISSR may be reduced if other flights pass through that region and create contrails. For such measures to have any perceivable effect, the airspace identified as an ISSR should be avoided as much as possible, with aircraft diverted vertically or horizontally. Such air traffic measures would have impacts not only on the deviated flights but potentially on the whole network. To date, limited studies have been done on mitigating all flights from forming contrails, and therefore system impacts are not yet understood, but could easily increase CO_2 more substantially than current individual flight trials suggest. The impact on flight level congestion also must be carefully assessed.

The other important area, as mentioned above, is the exact metric being used to determine the CO_2 vs non-CO_2 calculation. Re-routing a single flight may make climate sense if using a GWP20 metric, but not if using a GWP100 scale, where the CO_2 penalty may outweigh the contrail avoided.

The trade-offs between CO_2 and non-CO_2 emissions have been mentioned, but there are also trade-offs amongst types of non-CO_2 emissions. For example, some combustor technologies might reduce particulate matter, but increase NOx, and vice versa. New engine technologies with higher thermal and propulsive efficiency will reduce fuel burn and CO_2, but could be more contrail-prone. All these trade-offs and the impact of each climate forcer must be carefully understood. ICAO's Committee on Aviation Environmental Protection (CAEP) regularly assesses those aspects and proposes technical standards and methods to further understand and control emissions directly emitted by engines.

State of science: observing and forecasting ISSR

The most challenging aspect of identifying where ISSRs will form is understanding the relative humidity and temperature in any given region. Often these regions are relatively narrow bands of airspace: sometimes no more than a few hundred metres in vertical airspace (perhaps two flight levels) and extending over 100-200 km of horizontal airspace. Sometimes they can also cover a more significant region. In order not to simply block vast areas of useable airspace and to enable effective mitigation through adjustments of aircraft trajectory, current weather models require more humidity observation data to improve their accuracy. One option is to install sensors on board aircraft: there are already humidity sensors on commercial aircraft as part of the AMDAR and IAGOS projects. However, these are either not suited for accurately observing the required ice supersaturation, or the sensors are too cumbersome and sensitive for widescale deployment. There are additional uncertainties regarding the movement of contrails after formation that would require any changes in aircraft trajectory to account for these movements.

Identifying and forecasting the regions where persistent warming contrails will form is a fundamental building block to help the industry mitigate the effects. A key next step is to improve the quantity and quality of near-real-time water vapour observations in the upper troposphere.

Sensors are currently being developed that could be reliable and lightweight enough to be installed on a statistically significant proportion of the fleet. Further work is needed to industrialise these and propose them to airlines for installation on commercial aircraft. With a portion of the global fleet equipped, the granularity of humidity monitoring would improve significantly, making operational changes more accurate and, at the same time, improving general weather forecasting. However, the development of such a sensor will take a few years and once the technology is available, systems will need to be refined to ensure the data can be transmitted to weather forecasters to include in their models.

Several computer models have also been developed to try and forecast where ISSRs are likely to form ahead of time, but they still depend on data for evaluation or initialisation of the simulations which can lead to more accurate modelling capabilities[6]. While numerical weather prediction slowly continues to improve its ability to model the processes for cirrus cloud formation and persistence, many advancements are required in order to correctly predict when, where, and the extent of ice supersaturation[7].

Mitigation: operational contrail mitigation options

Once ISSR forecasting quality and the persistence and impact of individual contrails becomes sufficiently accurate for decision making, the operational solutions could be 'relatively simple': route some or all aircraft around, above or below these ISSRs. This could be done tactically (when flights are in the air, post-departure), or pre-tactically (during the flight plan stage, pre-departure). However, another area of research required will be the impact of these flight deviations on the airspace system as a whole: one or two flights re-routed can be accommodated, but if strategically significant areas of the airspace system, such as over Central Europe or the United States are blocked off, the CO_2 and congestion and safety impact could be large. Flying under an ISSR could put flights into more contact with unsettled weather and also increase turbulence episodes. While globally, it is believed that a small number of flights create the majority of the warming impact from contrails, when ISSRs are present in congested airspace the capacity and traffic impacts may be significant.

Despite some fundamental questions that remain to be answered, the aviation industry is already fully engaged with the research community to better understand the dynamics of contrail formation and the potential options for avoidance solutions once better observations and forecasting of ISSRs is enabled.

Some of the current operational avoidance trials include:

» **Air France, Meteo France:** Meteo France provided predictions of contrail-prone areas (ISSRs) and Air France undertook operational trails avoiding those regions. The number of flights were limited and a diversion was not always possible due to airspace constraints. The partnership is now working on a campaign for pilots to take photographs of contrails at altitude to verify and validate Meteo France's weather predictions.

» **Delta Air Lines, MIT:** Delta trialled avoiding contrails from certain flights and MIT used satellite observation of flights and contrails to verify weather models and the success of re-routings. Results from the trial have not yet been published in peer-reviewed scientific journals.

There is a significant amount of practical and operational research underway to prepare for mitigation options, once some of the fundamental questions have been resolved.

» **American Airlines, Google Research, Breakthrough Energy:** limited flight trials (around 70 flights) were conducted by American Airlines to determine contrail formation from certain flights using satellite observation of flights and contrails and AI in 'almost' real-time. Questions remain as to the methodology and usefulness of results due to difficulties in validating contrail avoidance, and uncertainties in the model and satellite observations.

» **Eurocontrol Maastricht Upper Air Centre (MUAC):** Overnight contrail avoidance trial. The study found challenges in determining the limits of horizontal bands of ISSR. Tactical simulations with controllers discovered some safety challenges and a potential 20% capacity hit.

» **Airbus, Meteo France, IAGOS, DLR, NLR, ONERA, UPC, Imperial College, Breakthrough Energy, Air France, Swiss Airlines, easyJet, NATS, DSNA, Eurocontrol, Boeing:** The SESAR-funded CICONIA project (2023-2026) develops mitigation Concepts of Operations and their assessment in comparison to legacy operations. CICONIA integrates CO_2 and non-CO_2 trade-offs, metrics, the integration of different climate models and aircraft specificities. Extensive simulations and trials in oceanic and continental airspace will be performed.

Mitigation: a role for alternative fuels?

Most types of sustainable aviation fuel (SAF) that are currently being promoted for the purpose of reducing CO_2 emissions also have a lower aromatic content than traditional fossil-based jet fuel. There is a direct correlation with the amount of carbon particulates emitted. Furthermore, some forms of SAF contain fewer sulphur compounds, which also impacts contrail properties. Research is ongoing to determine what the effect of these emission profiles would have. While SAF could cut particulate matter emissions by at least 50%, when used in its pure form, there would still be an order of magnitude of trillions of particles per kilogram of fuel burnt. Some studies have determined that despite this, SAF contrails might be more short-lived, but others believe that secondary effects due to smaller amounts of soot could take place and the benefits could be offset. In the future, the use of hydrogen as an aviation fuel would eliminate all particulate matter emissions, but it is thought that contrails could still be created and nucleate onto the already existing atmospheric aerosols.

Extensive research is currently underway by various bodies to determine how much of a contrail mitigating role the shift to SAF will provide[8]:

» **NASA, DLR, Boeing:** ACCESS-2 effects of SAF blends on cruise soot and contrail ice particles. The measurements showed a reduction of 50-70% in emitted particles when using a 50% HEFA SPK blend. (Moore et al., Nature, 2017). Contrail ice measurements have not been published.

» **NASA, DLR:** ND-MAX's mission to evaluate SAF blend effects on cruise soot and contrail ice particles (2018)[9] showed a reduction in both soot emissions and contrail ice particles formed when using SAF blends.

» **Airbus, DLR, Rolls-Royce, Neste, Manchester Metropolitan Uni, Safran, NRCC + Airbus, DLR, Safran, Dassault, ONERA, French Ministry of Transport:** ECLIF3 and VOLCAN are two extensive flight campaigns led by Airbus and DLR focussing on measuring direct emissions and contrail formation / properties, as well as aircraft performance and SAF compatibility by analysing, comparing and evaluating the effects of different fuels (100% SAF and SAF blends). Results will support research on better understanding and quantifying climate impacts of SAF compared to conventional fuels.

» **Boeing, NASA, GE, DLR, FAA 2023 EcoDemonstrator:** Over 100 combined DC8 and 737-10 flight hours and 2 days of ground testing studied how the combination of SAF and the advanced lean-burn CFM LEAP-1B engines on the 737-10 impact engine particle and gas emissions and characterised how reducing soot emissions and fuel sulphur affect the number of contrail ice particles produced under a range of atmospheric conditions.

» **Pratt & Whitney, Missouri University of Science and Technology, Aerodyne Research, US EPA and FAA ASCENT project:** A Geared Turbofan engine combustor rig test stand will be used to enable further understanding of the emissions benefits of SAF, including reduced sulphur dioxide and non-volatile particulate emissions, which are associated with contrail formation.

Mitigation: regulatory environment and challenges

The European Union's Directorate-General for Climate Action (DG CLIMA) is embarking on an effort to require aircraft operators to collect and report data on non-CO_2 emissions from flights departing European Union airports. The system is currently being developed and is intended for use from 1 January 2025 with a review following several years of monitoring to determine further action (including incorporating non-CO_2 into the EU Emissions Trading Scheme). Industry believes it is premature for the application of such a system and, given many of the questions outlined in this paper, if it could even be operationalised to avoid contrails. Recent publications have shown that reanalysing data to backcast the creation of a contrail could be wrong 50-80% of the time, and the uncertainty on the climate impact of individual contrails could be two orders of magnitude higher than the uncertainty of the global fleet[10].

The DG CLIMA Non-CO_2 data collection will likely not produce data which will be useful to operationalise the avoidance of contrails: application of additional regulation in this area is premature until trials are able to assess the optimum approach. It also assumes that contrail mitigation should be done on a flight-by-flight basis, which may not be the most appropriate method: testing and trials should preceed regulatory action. Focus should also be given to the identification and forecasting of ISSRs so that these areas of airspace can be avoided.

Industry supports

Continued academic and technical research into:

- Overall contrail impact on warming and understanding of the formation and warming mechanisms.
- Other parts of the non-CO_2 question, including NOx and SOx.
- Humidity sensors (to commercialise for use regularly during flights).
- Improving weather / ISSR prediction models and verification efficacy.
- Understanding the impact of alternative fuels as a mitigation tool.

Large-scale operational trials on contrail avoidance

- Multiple trials should take place, with global coordination to maximise resource efficiency and knowledge sharing.

Industry **does not** support

Regulation moving ahead of science

- Including regulating the collection of data without a clear contrail mitigation pathway in sight.

Daily / continual operationalisation of contrail avoidance across the system

- (until trials have yielded results to ensure a better understanding of CO_2 trade-offs, flight operational impacts, efficacy of mitigation methods, etc...).

The monetisation of contrail avoidance

- The creation of carbon credits from the avoidance of contrails is premature until more certainty exists over verification of avoidance.

Deliberate creation of cooling contrails

Core unanswered questions and concerns for industry

» Some proposed solutions or policy considerations seem to 'monetise' the avoidance of contrails, comparing them with CO_2 equivalent factors. Industry is not currently supportive of this approach, given the difficulty in establishing that a contrail (and more importantly an impactful, persistent, contrail) has been avoided. This is in addition to the other uncertainties highlighted above.

» Individual flight shifts (or airline-by-airline actions) to avoid contrail formation are already being trialled. But what happens when we try to shift all flights in a crowded airspace system (for example over Central Europe, the North Atlantic or the US)? Is such widescale avoidance in busy airspace safe and viable? Does the resulting congestion and increased CO_2 emissions outweigh the contrail impact? Furthermore, those individual experiments have shown the difficulties in validating whether a contrail was avoided through re-routing. Finally, measures are also needed to ensure that contrail avoidance does not result in an increase in flights experiencing hazardous turbulence.

» Most discussions focus on the fact that identifying the exact ISSRs / areas of humidity is one of the biggest challenges: monitoring of those regions would allow the solutions to be rolled out. Can we focus for the short-term on encouraging better monitoring / sensors whilst also conducting avoidance trials?

» There are some suggestions to not only try and avoid warming persistent contrail formation, but to intentionally generate cooling contrails. Industry is very concerned about the potential unintended consequences of this approach. Industry supports efforts to avoid contrail formation, as they are developed, but would not want to intentionally create them.

Requests for government support

Whilst scientific and operational mitigation questions remain, the industry is committed to reducing its climate impacts, including from contrail formation. Importantly, industry and governments must work together to operationalise modelling and simulations developed by the research community. The following recommended steps have been identified for governments:

» Continue funding scientific research into contrail impacts to reduce the uncertainties identified in this paper, investing in research to better understand the trade-offs between the warming and cooling effects of contrail cirrus clouds, with the aim of providing the best available information for climate-optimised flight operations and avoiding unwanted warming effects.

» Expand support for larger-scale operational demonstrations of contrail avoidance systems to enable a better understanding of airspace implications and potential increases in CO_2 emissions from re-routing.

» ICAO CAEP could undertake an assessment of the correct metrics and timeframes could be used as part of this process, noting that GWP100 is the basis for most UNFCCC assessments and the basis for the long-term goals underpinning the Paris Agreement. CAEP should continue to convene its Impacts and Science Group (ISG) to provide the best possible consensus from the research community on the climate impact from aviation's non-CO_2 emissions, including interdependencies and trade-offs linked to potential mitigation options.

» Continue support for investigating the effects that alternative fuels such as SAF and hydrogen have on non-CO_2 emissions. SAF production must to be ramped up significantly as part of the sector's efforts to address CO_2.

- Improve humidity forecast data, which is crucial to achieving higher quality ISSR forecast data in collaboration with weather services. This could include support for the development and deployment of humidity sensors (or improvements in satellite observation technology) to identify ISSRs – sensor development is already underway but should be sped and scaled up for deployment. In the US, the Department of Energy ARPA-E PRE-TRAILS programme is making progress with several suppliers. Once the most appropriate sensors can be placed on aircraft, a comprehensive roll-out with agencies such as the World Meteorological Organization (WMO) will be needed to coordinate the data into useable forms and with funding support for the assimilation programme.

- Investigate operational and policy solutions that are specifically for non-CO_2 climate impacts, taking account of their behaviour differences compared to CO_2 emissions and the distinct challenges they represent for the sector. In particular the use of tools designed for CO_2 management (such as emissions trading schemes) are not suitable for mitigating non-CO_2 impacts. This includes avoiding inappropriate simple multipliers for CO_2 to account for non-CO_2 impacts that do not reflect the complexity of the non-CO_2 phenomena.

- Prioritise actions that lower both non-CO_2 and CO_2 emissions (e.g. operational decisions).

- Recognise that the prevalence of non-CO_2 climate impacts from persistent contrails varies greatly from region to region and from day to day, as it is a highly heterogeneous phenomenon that requires a more bespoke approach, while the effects of CO_2 emissions are homogeneous regardless of geographical location.

- Develop practical, implementable and robust concepts that incentivise persistent contrail cirrus avoidance without compromising safety. These will be investigated further once the uncertainties have been resolved.

Further reading

- *Eurocontrol and CANSO Sustainable Skies Conference, November 2023:* ***https://tinyurl.com/bdpy8far***
- *IATA, Aviation Contrails and their Climate Effect, April 2024:* ***https://tinyurl.com/29ve3her***
- *Airlines for America, Addressing Non-CO_2 Emissions from Aviation, April 2024:* ***https://tinyurl.com/uedn4nv6***
- *Airlines for Europe, Non-CO_2 MRV Position Paper, August 2023:* ***https://a4e.eu/wp-content/uploads/A4E-Position-Paper-and-Recommendations-Non-CO2-MRV-FINAL.pdf***

[1] ICAO Assembly/41 Resolution, 2022: www.icao.int/Meetings/a41/Documents/Resolutions/10184_corr_en.pdf

[2] Ice super-saturated regions (ISSRs) are areas of the atmosphere where the conditions exist for contrail formation. Sometimes these will be short-lived contrails, sometimes long-lived.

[3] Although the industry has historically focused on reducing smoke number (as a proxy for particulate matter mass concentration), it has also taken steps to reduce total soot mass emissions and total soot number (particle counts). However, there are also some uncertainties associated with modelling cruise soot emissions, especially soot number (particle counts), and uncertainties around contrail / ice crystal formation in low-soot regimes: these elements are part of extensive research into the solutions for contrail avoidance.

[4] Global aviation contrail climate effects from 2019 to 2021, in *EGUsphere*, 2023 [preprint]: https://doi.org/10.5194/egusphere-2023-1859

[5] Uncertainties in mitigating aviation non-CO_2 emissions for climate and air quality using hydrocarbon fuels in *Environmental Sciences: Atmospheres*, November 2023: https://pubs.rsc.org/en/content/articlelanding/2023/ea/d3ea00091e

[6] IATA *Aviation Contrails and their Climate Impact*, April 2024: www.iata.org/contentassets/726b8a2559ad48fe9decb6f2534549a6/aviation-contrails-climate-impact-report.pdf

[7] How well can persistent contrails be predicted? in *Aerospace 7*, no. 12, 2020: https://doi.org/10.3390/aerospace7120169; and How well can persistent contrails be predicted? – an update, in *EGUsphere* [preprint], 2024: https://doi.org/10.5194/egusphere-2024-385.

[8] Reference studies: www.nasa.gov/news-release/nasa-dlr-study-finds-sustainable-aviation-fuel-can-reduce-contrails/; www.nature.com/articles/s43247-021-00174-y; and https://egusphere.copernicus.org/preprints/2023/egusphere-2023-2638/

[9] Cleaner burning aviation fuels can reduce contrail cloudiness, *Nature Earth and Environment*, 2021: www.nature.com/articles/s43247-021-00174-y; and Reduced ice number concentrations in contrails from low-aromatic biofuel blends, *Atmospheric Chemistry and Physics*, 2021: https://acp.copernicus.org/articles/21/16817/2021/acp-21-16817-2021-discussion.html

[10] Mitigating the Climate Forcing of Aircraft Contrails by Small-Scale Diversions and Technology Adoption in *Environmental Science and Technology*, 2020: https://core.ac.uk/download/pdf/322489934.pdf

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