Defining a way forward for the science and technology of contrail mitigation

A report from
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Foreword

This report reviews the current scientific understanding on aviation contrails, their climate impacts, and mitigation strategies. It assesses recent advances, knowledge gaps and remaining scientific and technological challenges. The aim is to inform the development and operational deployment of contrail avoidance strategies. This report primarily addresses the atmospheric and climate science dimensions, while acknowledging that the ATM and policy dimensions should also be taken into account.

Executive summary

Aviation influences the global climate through a combination of carbon dioxide (CO_2) emissions from fuel combustion and several non-CO_2 effects. Among these non-CO_2 contributors, condensation trails (contrails) and the resulting contrail-induced cirrus clouds are identified as a strong warming factor, exerting a radiative forcing that is comparable to the cumulative impact of aviation's CO_2 emissions. Because contrails are inherently short-lived, with lifetimes often ranging from minutes to 12 hours, successful mitigation offers a unique opportunity to reduce aviation's radiative forcing relatively rapidly, providing tangible climate benefits within less than a decade.

A defining characteristic of the contrail problem is its high level of concentration: estimates suggest that only 2-3% of all flights are responsible for 80% of the total warming caused by contrails worldwide. This disproportionate impact creates a strategic window for targeted interventions, such as modest adjustments in flight altitude or routing, which can prevent aircraft from entering ice-supersaturated regions (ISSRs) where persistent contrails form. However, the benefits of contrail mitigation must be complemented by sustained reductions in CO_2 emissions over the medium to long term, as the climate system's response to contrails is short-lived and the benefits of contrail mitigation would rapidly diminish if such efforts were discontinued.

The physical principles governing contrail formation are well-established and depend both on exhaust characteristics and atmospheric conditions. Both engine technology and fuel composition play critical roles, as soot and other particles provide the nucleation sites for ice crystals. Research demonstrates that reducing soot emissions through alternative fuels has the potential to lower contrail-cirrus related climate impacts but may result in unintended effects at very low emission rates of particles.

Despite these insights, several critical knowledge gaps persist. Quantifying the net radiative impact is complicated by the trade-off between solar cooling and terrestrial warming during the day but also creates some opportunity to mitigate nighttime-only contrails whose impact is comparatively more certain. The extent to which the climate impacts of individual contrails adds up or not is also uncertain and may limit the efficiency of contrail avoidance strategies based on rerouting individual flights. A notable area of uncertainty concerns atmospheric adjustments whereby contrails deplete upper-tropospheric humidity and suppress natural cirrus formation.

Furthermore, there is also some uncertainty regarding the contrail efficacy, as contrail-induced radiative forcing may have a smaller impact on global surface temperatures than an equivalent amount of CO_2 forcing.

Operationalizing mitigation involves several stages of planning, from flight scheduling months in advance based on climatological averages to real-time tactical rerouting. Airline-led strategies may focus on individual flight optimization and are particularly effective for nighttime operations where the warming effect is most certain. In contrast, Air Traffic Management-led approaches may be better suited for high-density traffic regions as they can manage entire airspaces to avoid contrail-prone zones. Use of sustainable aviation fuels or other alternative fuels could be targeted to flights predicted to have a high contrail warming potential to maximize their climate benefit. Such fuels can reduce soot particle emissions, leading to contrails with fewer ice crystals and lower radiative impact in the case of conventional rich-burn engines.

Recent small-scale trials have demonstrated the feasibility of rerouting flights to avoid contrails, with some measurable benefits on contrail radiative impacts and a relatively low increase in fuel burn. However, these trials typically involve only ten to a hundred flights, which is insufficient to encompass the full diversity of atmospheric conditions and aircraft types. The path forward requires transitioning to a handful of large-scale trials involving thousands of flights across different airspaces to rigorously verify climate benefits and operational impacts.

A central challenge for wide-scale implementation is the current limitation of meteorological models in accurately forecasting the vertical structure of ice-supersaturated regions. While numerical weather prediction models show a level of skill that is sufficient for current trials, contrail mitigation strategies will benefit from improved prediction of upper-atmosphere humidity. Improving these forecasts will require the integration of new data sources, such as low-maintenance humidity sensors permanently installed on commercial aircraft, which would sample the exact flight levels where contrails are most likely to form.

Finally, contrail mitigation strategies require a trustable digital twin framework to simulate and verify the climate impact of mitigation measures against agreed benchmarks. This tool would combine physically-based models with observational data to simulate avoidance strategies and ensure they are delivering real climate benefits. Success will depend on closer collaboration between the aviation industry and the meteorological community to refine nowcasting capabilities and establish transparent, open-access datasets for ongoing research.

A substantial body of research on contrail avoidance is already available and provides a strong foundation for future operational deployment. While some research gaps remain, this report sets out the following recommendations to support both future scientific advances and progressive operational implementation:

1. Focus on the uncertainties that matter. Not every single uncertainty on contrails matters. Future studies should target areas of uncertainties that matter for quantifying the climate impact of contrails and designing effective contrail mitigation strategies.

This report identifies four main areas of uncertainties that should be looked at: properties of fresh contrails, contrail radiative impact, contrail-contrail interactions, and atmospheric adjustments. These correspond to key processes linking contrails to their climate effects.

2. Encourage open-access contrail datasets. A coordinated framework should be established to systematically expand existing open-access datasets from ground-based cameras and satellite sensors to include co-located spaceborne lidar–radiometer measurements and high-resolution imagery, enabling rigorous evaluation of contrail impact models.

3. Intercompare contrail process models. The scientific community should launch coordinated model comparison exercises based on common experimental frameworks. Some of the model experiments should seek to represent real-world cases so that observations can be used to assess model performance. and real-world observational cases. This will help to quantify the robustness of predicted contrail radiative impacts under different meteorological conditions.

4. Bridge radiative transfer calculations and observations. There is a need for reference calculations of how contrails interact with solar and terrestrial radiation. Such calculations should explicitly account for contrail spatial inhomogeneities, three-dimensional effects, and interactions with the contrail environment. They should be confronted with direct observations of contrail radiative impact.

5. Resolve the radiative forcing-temperature relationship. Efforts must be strengthened to quantify atmospheric adjustments and narrow the uncertainty in the climate efficacy of contrail cirrus. This could involve coordinated climate model experiments, potentially under the auspices of the Climate Model Intercomparison Project (CMIP).

6. Conduct more flight tests to study the impact of alternative fuels on contrail formation. Further targeted field campaigns, including dedicated flight tests, are required to advance our understanding of ice nucleation during initial contrail formation for alternative fuels such as sustainable aviation fuels and hydrogenated kerosene across multiple engine technologies and representative meteorological conditions.

7. Consolidate strategies for large-scale contrail avoidance trials. Future trials must be conducted in a transparent and coordinated manner using standardized guidelines for selecting reference flights and evaluation frameworks. Large-scale trials lasting at least a year are necessary to account for the wide range of atmospheric situations and aircraft types.

8. Investigate humidity sensors onboard commercial aircraft. To improve observations of ice-supersaturated regions beyond current satellite capabilities, low-maintenance, permanently integrated humidity sensors should be deployed on commercial aircraft. Requirement definitions for these sensors should be guided by Observing System (Simulation) Experiments.

9. Improve Numerical Weather Prediction forecasts. Existing models should be intercompared and enhanced with improved physical representations and further data assimilation of humidity observations. Hybrid AI-driven nowcasting should also be developed to complement traditional forecasts for tactical avoidance.

10. Develop a contrail avoidance digital twin. Operational mitigation requires a digital twin to simulate the climate impact of contrails and avoidance measures. This tool, whether physics-based or data-driven, must remain unbiased against benchmark datasets to ensure the most targeted and cost-effective avoidance strategies.

I. Introduction

Aviation contributes to global warming through several pathways. The most widely recognised one is the release of carbon dioxide (CO_2) associated with the combustion of kerosene[1,2,3]. In 2018, i.e. before the Covid pandemic, global civil aviation emitted an estimated 918 millions of tons (Mt) of CO_2 (ref. 4), representing about 2.5% of the 36 billions of tons (Gt) of CO_2 released from fossil fuels in the atmosphere worldwide that year[5]. Traffic decreased during Covid but has resumed its growth since then with emissions now above pre-Covid levels[6].

Aviation non-CO_2 climate effects

Beyond CO_2, the principal emissions of aircraft include nitrogen oxides (NO_x), water vapour, and microscopic particles (such as soot and sulphate aerosols)**. Under suitable atmospheric conditions, the emission of water vapour and particles can further lead to the formation of condensation trails (contrails).** These emissions result in a whole range of chemical and radiative processes that eventually contribute to influence the climate, as illustrated in Figure 1. These processes and their climate impact are collectively referred to as aviation non-CO_2 effects[7,8] as they occur independently of the CO_2 emissions.

Nitrogen oxides alter the cleansing capacity of the atmosphere, leading to short-term increases in tropospheric ozone and longer-term decreases in atmospheric methane. As both ozone and methane are greenhouse gases, these changes produce partly compensating effects, with the warming from increased ozone currently outweighing the cooling effect from reduced methane. Water vapour emissions at cruise altitudes also play a role, especially when emitted into the lower stratosphere where it is more long-lived and exerts an additional greenhouse effect. In addition, the formation of condensation trails (contrails) and contrail-induced cirrus clouds modifies the atmospheric radiative balance by reflecting solar radiation and by trapping heat. Particulate emissions, primarily soot and sulphate aerosols, further influence cloud microphysics and can also modulate both contrail formation, cirrus cloud properties, and other clouds downwind of the aircraft trajectories. Some of these effects contribute to a net warming of the climate system, while others induce a net cooling. They are subject to some uncertainties, as well as pronounced regional and temporal variability. Aviation non-CO_2 effects are heterogeneous in nature, and mitigation options are generally specific to each mechanism; consequently, there is limited justification for treating them as a single, unified category. Among non-CO_2 effects, **contrails stand out as the single largest contributor to warming, while also offering substantial opportunities for targeted mitigation.**

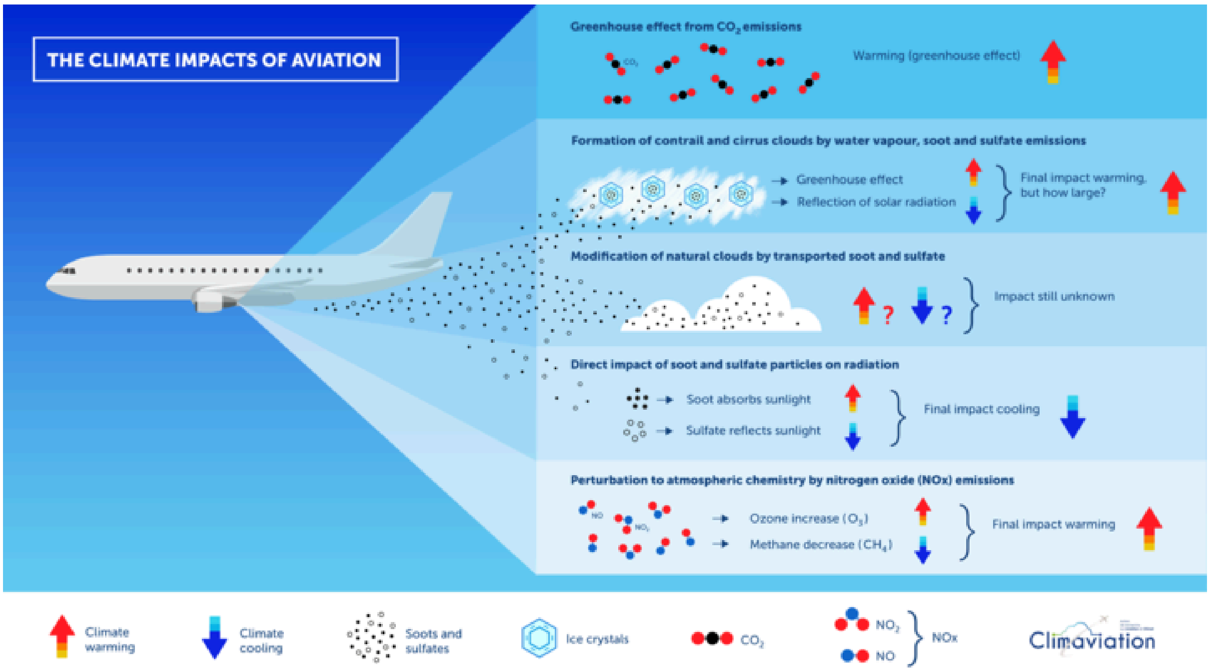


Figure 1: Schematic overview of aviation climate effects, with CO_2 emissions shown in the top row and non-CO_2 effects associated with other emissions shown in the rows below. Adapted from Climaviation (https://climaviation.fr/en/).

Contrail formation: a complex interplay of atmospheric processes

Aircraft contrails are line-shaped clouds formed when water vapour from aircraft exhaust mixes with the cold, humid air of the upper atmosphere. Depending on how cold and how humid the atmosphere is, contrails can either dissipate rapidly or persist and spread into extensive cirrus layers. Three types of contrails can be observed in the atmosphere: non-persistent contrails, persistent contrails and contrail cirrus as shown in Figure 2. These cloud layers influence the Earth's radiative balance that govern its climate. **By nature, non-persistent contrails dissipate rapidly after formation and cover only a very small fraction of the Earth's surface. Consequently, most attention is focused on persistent contrails and their subsequent evolution into contrail-induced cirrus clouds.**

Contrails are inherently short-lived phenomena. Typically, contrails are considered persistent when their lifetime exceeds about 10-15 minutes. Persistent contrails can then evolve into contrail-induced cirrus clouds over timescales ranging from ten minutes to a day[9,10]. Some contrail cirrus outbreaks can be tracked for up to approximately 12 hours[9,11], although they may become difficult to distinguish from natural cirrus clouds after a few hours. As a result, the climatic impact of a contrail cirrus outbreak is generally estimated over a period of typically 12 hours.

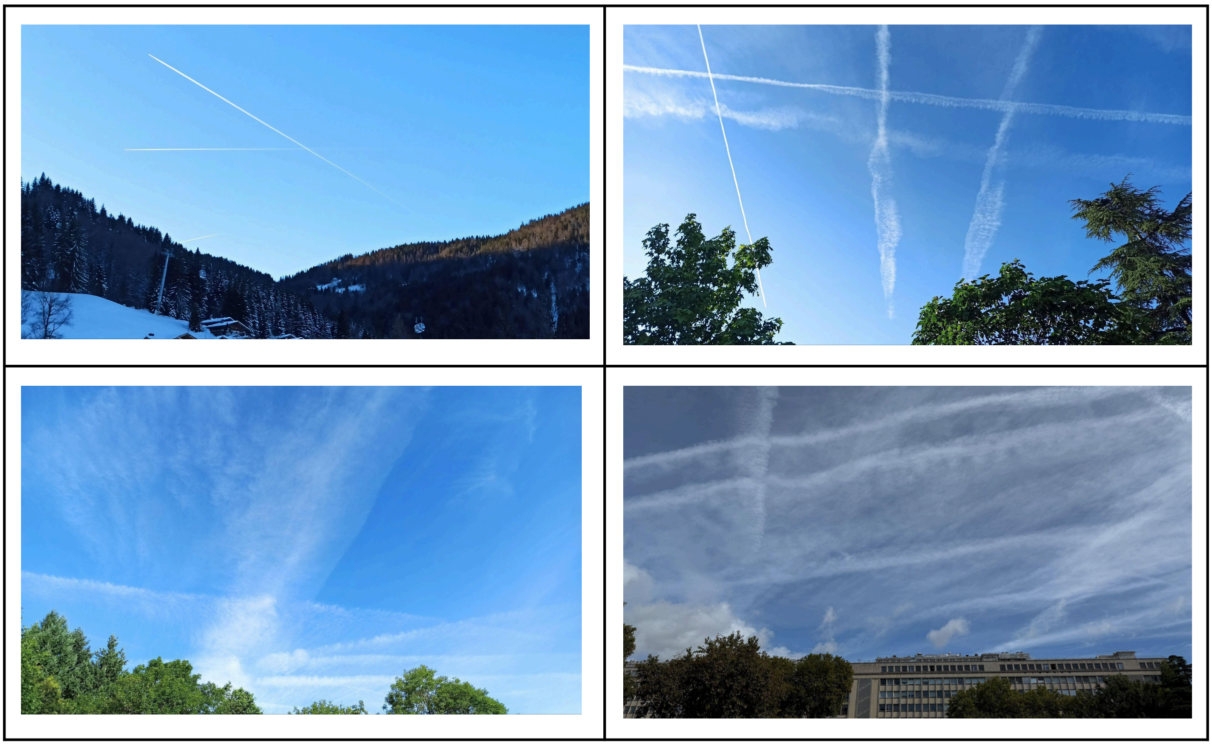


Figure 2. Various types and stages of contrails (from top left to bottom right): non-persistent contrails, persistent linear contrails, contrail cirrus, contrail cirrus embedded in natural cirrus. © Audran Borella.

Persistent contrails and contrail outbreaks occur in so-called ice-supersaturated regions (ISSRs). These are patches of air in the upper troposphere (located between 7 and 11 km altitude) that contain unusually high amounts of moisture[12]. Such patches are not permanent: they appear, move, and disappear depending on weather systems. They typically extend over 10 to 100 km horizontally but they often cluster in regions that can be several hundred kilometers long or more[13,14]. Vertically, they are relatively thin, generally spanning layers of 0.5 to 1 km (and occasionally more), which typically corresponds to a thickness of 2000 to 6000 feet. An air mass that becomes ice supersaturated typically remains so for several hours but a fraction remains ice supersaturated for at least 24 hours[15].

Persistent contrails and contrail-induced cirrus generally exert a warming effect on climate by trapping terrestrial heat. Technically, contrail cirrus decreases the amount of terrestrial radiation that escapes to space in a similar way to greenhouse gases, but much more efficiently[16]. In addition contrail cirrus reflect a small fraction of solar radiation, which causes a cooling effect that may partially offset or even exceed their greenhouse effect. Obviously the effect on solar radiation only takes place during daytime. The magnitude of contrail radiative forcing thus depends on a range of factors, including flight altitude, meteorological conditions, aircraft type, and characteristics of the plume coming out of the engine, and for the solar effects, the position of the Sun in the sky and the reflectivity of the surface. **Understanding contrail formation, evolution, and how they are embedded in their environment is**

therefore essential for assessing the radiative and climate impacts of contrail cirrus and for designing effective contrail avoidance mitigation strategies.

Why mitigate contrails?

Contrails occupy a particularly prominent place among the non-CO_2 climate effects of aviation. **Contrails and contrail-induced cirrus clouds exert a net warming effect on the climate system, with an associated radiative forcing[17] that is uncertain but comparable to that induced by aviation CO_2 alone[18]**. Moreover, their impact is highly unevenly distributed: a relatively small fraction of flights is responsible for the majority of contrail-related climate forcing. It is typically estimated that 2-3% of the flights generate 80% of the warming due to contrails worldwide[19] but it could be significantly more at the regional or seasonal level[19,20]. For instance, in wintertime, 20% of the flights may generate 80% of the impact over the transatlantic route. This concentration opens a window of opportunity, as targeted operational changes, such as modest adjustments in flight altitude or routing, can substantially reduce contrail formation and persistence. As a result, **contrails potentially represent a tangible opportunity for mitigating the climate footprint of aviation.**

By targeting a short-lived climate forcer, contrail mitigation could reduce the radiative forcing due to aviation relatively rapidly, delivering climate benefits within decades. This is because the climate system only has a limited memory of past contrail-induced cirrus and adjusts to changes in their occurrence on such timescales. **However, the benefits of contrail mitigation efforts would diminish rapidly if they were ramped up and then discontinued in the future, underscoring the need to pursue CO_2 reduction measures in parallel** to ensure long-term climate benefits and to establish a credible roadmap towards sustainable aviation.

From early proposals to current strategies

Initial proposals[21,22] for contrail mitigation dates back from the early 2000s and focused on systematically modifying flight altitudes to avoid ice-supersaturated layers conducive to contrail formation. It was soon recognised that such an approach is generally inefficient because aircraft operate near their fuel-optimal cruise altitude. Routinely operating aircraft at a lower flight level to avoid ice-supersaturated layers that occur only a small fraction of flight time would therefore result in unnecessary additional fuel burn and CO_2 emissions.

Since then, many studies have tried to refine the concept of contrail avoidance, however most of these studies have focused on a particular aspect, such as vertical rerouting extent[23,24], flight rescheduling[25], sensitivity to contrail-CO_2 equivalence[26,27], utility of partial contrail avoidance[28], flight path optimization tools[29], practical feasibility of rerouting for airlines[30,31,32,33], impact on airspace capacity[34], ... **Current research and operational thinking have broadened the range of possible interventions,** spanning the planning time scales (months to years ahead, e.g. route network design and fleet planning), strategic and pre-tactical time scales (days to hours ahead, e.g. flight planning and weather-dependent trajectory optimization), and tactical time scales (minutes to hours, e.g. pre-flight or in-flight adjustments in response to updated atmospheric conditions). Strategies should assess the relative roles of lateral and vertical flight adjustments, the design of meteorology-aware contrail-avoidance strategies, and distinctions between airline-led and air-traffic-management-led approaches. **In addition, contrail formation can be influenced through fuel composition and alternative fuels, opening new pathways for contrail management.** However a complete picture of the potential, cost and effectiveness of integrated contrail avoidance strategies is still lacking.

Motivation for this report

This report builds on the scientific literature and previous reports on contrail formation, contrail mitigation potential and contrail avoidance strategies. It will identify which aspects, from contrail formation to their climate impacts, are now well understood, and which ones remain affected by scientific uncertainties. Most importantly the focus will be on identifying uncertainties that matter for a successful and effective deployment of contrail mitigation strategies at scale, rather than on advancing contrail science for its own sake. The report will also highlight existing knowledge and technological gaps that currently limit the reliability of contrail prediction, contrail detection, and contrail mitigation approaches. Building on this assessment, **the report will provide targeted recommendations for future research and development priorities, with the aim of advancing scientific understanding in a way that would benefit the operational deployment of robust contrail avoidance measures.**

What's in this report?

We first assess the potential for contrail mitigation in order to provide further justification for the current focus on contrail avoidance. We then summarise the current state of knowledge on the physics of contrails before presenting a set of recommendations to advance contrail science and assess the criticality of remaining uncertainties for contrail avoidance and management strategies. Finally, we examine the technological enablers required for operationalising contrail mitigation, together with the lessons learned from past contrail avoidance trials, in order to formulate additional recommendations supporting operational deployment. The report ultimately proposes a roadmap aimed at strengthening the scientific foundations of contrail research and advancing the enabling atmospheric technologies required for operational contrail avoidance.

II. Potential for contrail mitigation

Assessing the potential for contrail mitigation first requires the selection of suitable indicators. A difficulty arises because the most important greenhouse gases[74] are long-lived in the atmosphere while the atmospheric effects of contrails and contrail cirrus dissipate much quicker after typically a few days. This difference in timescales between CO_2 and contrails has triggered a lot of discussion, and sometimes controversy, on how to measure their respective effects. However it should be made clear that the short lifetime of contrails is counterbalanced by their very strong warming effect during the period in which they persist[16].

Choice of climate metrics: a scientific or political choice?

Converting the climate impacts of contrails into CO_2-equivalent emissions requires the selection of a suitable climate metric. In practice, the climate impact of contrail cirrus associated with a given flight, or a class of flights, is expressed relative to that of CO_2 using the chosen metric; the flight's CO_2 emissions can then be multiplied by this ratio to obtain a CO_2-equivalent value. A wide range of climate metrics has been proposed for aviation contrails (Figure 3). **Climate metrics usually specify (i) an indicator (often a physical climate quantity) and (ii) a time horizon to express what aspect of the climate system they emphasise and for how long or when.** Global Warming Potential (GWP) quantifies the perturbation to the Earth's energy balance over some period while Global Temperature change Potential (GTP) quantifies the resulting change in surface temperature at some point in time. The Average Temperature Response (ATR) also quantifies the change in surface temperature but as an average over a time period rather than at the end of this time period. The choice of shorter time horizons favour short-lived climate forcers such as contrail cirrus over CO_2. Time-averaged metrics such as GWP and ATR also favour short-lived climate forcers compared to end-point metrics such as GTP. For radiation-based metrics, it makes sense to weigh the climate efficacy of contrail cirrus into the climate metrics, i.e. if contrail cirrus are less effective than CO_2 on a RF/ERF basis, then this should be taken into account in their CO_2 equivalence. One such example is the efficacy-weighted global warming potential (EGWP).

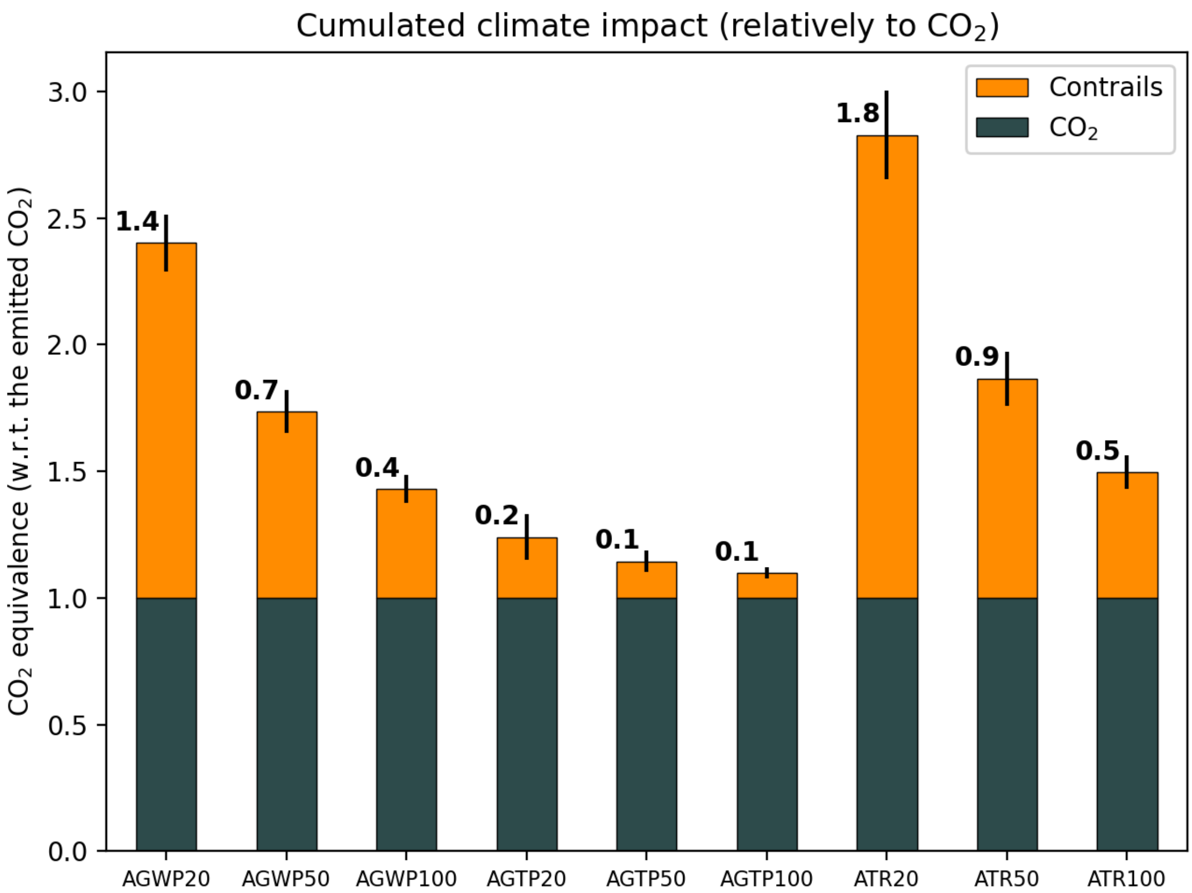


Figure 3. CO_2 equivalence of a median contrail (orange) compared to the emitted CO_2 during a typical North Atlantic flight (grey) when using absolute global warming potential (AGWP), absolute global temperature change potential (AGTP), and average temperature response (ATR) with time horizons of 20, 50, and 100 years. The values at the top of each bar are the ratio of non-CO_2 to CO_2 effects for each metric choice. Adapted from Ref. 27.

It is sometimes argued that, because mitigation of short-lived climate forcers can lead to a relatively rapid climate response, a shorter time horizon should be applied to these forcers. This is why ATR20, ATR50, GWP20, GWP50 are often put forward for measuring the benefit of contrail avoidance strategies. This reasoning is, however, ill-advised, as the choice of metrics should be guided by both scientific considerations and the policy goal. Because the climate system responds rapidly to a change in contrail does not mean that the policy goals should be changed.

It is more important that the climate metric used for contrail avoidance fits in the general framework for climate policy. In this context, guidance from the Paris Agreement is particularly relevant. **The Subsidiary Body for Scientific and Technological Advice (SBSTA) of the UNFCCC consistently identifies GWP100 as a robust and widely accepted metric under current policy frameworks**[36]**. The GWP metric can be combined with the lower-than-unity climate efficacy of contrail cirrus for a fairer comparison to CO_2, which results in the EGWP metric.** The European non-CO_2 Monitoring, Reporting and Verification (MRV)[37] considers three different time horizons for the EGWP (EGWP20, EGWP50 and EGWP100), which implies a range to measure the climate benefits of contrail avoidance.

The choice of climate metric generally has little influence on the decision of whether to reroute an individual flight for contrail avoidance, because the additional fuel burn associated with rerouting (in the region of 1%) is small compared to the estimated climate benefit of avoiding contrails which is many times more, regardless of the metric used[27]. However, the selected metric can affect the climate-optimal trajectory or the spatial extent of the airspace to be avoided, and thus the associated fuel penalty for a particular rerouting. It would also affect how contrail avoidance is being reported and incentivised. In practice, operational implementations of contrail avoidance are likely to impose an upper bound on acceptable fuel penalties, which would contribute to constrain rerouting options and reduce the sensitivity of rerouted trajectories to the specific climate metric chosen.

In summary, although somewhat still controversial, the choice of climate metric is not considered here to be a major source of uncertainty for operationalising contrail avoidance strategies. However it will influence the trade-off between contrail avoidance and fuel penalty, especially if larger (>1%) fuel penalties for individual rerouted flights are deemed acceptable. The EGWP100 metric is recommended here and used in this report, in particular for consistency with other climate legislation such as the Paris Agreement.

Estimating contrail mitigation potential

A prerequisite for assessing the mitigation potential of contrail strategies is a robust quantification of the climate impact of contrails. This is typically achieved using climate models, but complementary bottom-up estimates are also required to ensure consistency and to avoid double counting, particularly in cases where contrail effects may be non-additive, e.g. due to contrail-contrail interactions.

Table 1 summarizes available estimates of contrail RF and ERF. We focus on estimates published after the meta-analysis of Lee et al[18] in 2021. Some diversity in the estimates remains, reflecting current uncertainties, but there is some consistency for RF to lie in the range of 30 to 100 mWm^{-2}. Table 2 summarizes all published estimates of the contrail efficacy factor. The values differ significantly, but a best estimate of 0.37, corresponding to the average of the three contrail efficacy estimates, can be used.

These estimates can be converted into approximate estimates of the mitigation potential of contrail reduction using two climate indicators directly relevant to the Paris Agreement: tons of CO_2eq and °C of global warming.

Reference	RF (mWm^{-2})	ERF (mWm^{-2})	Comments
Lee et al. (2021)[18]	111 [33-189]	57 [17-98]	Meta-analysis for 2018 traffic.
Gettelman et al. (2021)[38]		62 [3-121]	Estimate for 2019 air traffic.
Bier and Burkhardt (2022)[39]	70 [50-78]		Estimate for 2006 air traffic is 44 [31-49] has been scaled for 2018 air traffic.
Teoh et al. (2024)[19]	62 [35-75]		Estimate for 2019 air traffic.
Märkl et al. (2024)[40]	72		Estimate for 2018 air traffic.
Perini et al. (2025)[41]	46 [30-66]		Estimate for 2019 air traffic.
Zhang et al. (2025)[42]		60	Estimate for 2018 air traffic. The authors used two different climate models.
		41	

Table 1. Published estimates of the simulated contrail RF and ERF.

Reference	Contrail efficacy	Remark
Ponater et al. (2005)[43]	0.59	Traffic is increased artificially to increase signal-to-noise. The value is calculated for short-lived linear contrails.
Rap et al. (2010)[44]	0.31	Traffic is increased artificially to increase signal-to-noise. The value is calculated for short-lived linear contrails.
Bickel et al. (2020)[45]	0.35	Traffic is increased artificially to increase signal-to-noise. The value is an ERF/RF ratio.
Lee et al. (2021)[18]	0.42	Corresponds to the average of the three previously published estimates, assuming that the ERF-based efficacy is equal to 1.
Bickel et al. (2025)[46]	0.21	Traffic is increased artificially to increase signal-to-noise.

Table 2. Published estimates of the contrail efficacy.

Tons CO_2eq are obtained using the EGWP100 metrics for reasons explained above and a contrail efficacy of 0.37. A radiative forcing of 30 mWm^{-2} converts[47] into 135 $MtCO_2$eq while a RF of 100 mWm^{-2} converts into 450 $MtCO_2$eq for the year 2018. **Assuming 50% effectiveness for contrail avoidance translates into emissions reductions of 67-225 $MtCO_2$eq annually for the current level of air traffic.** The fractions of contrail mitigation potential attributable to different regions of the world depend on the attribution method.

Phased contrail mitigation starting in 2030, targeting 50% effectiveness by 2040, results in an avoided temperature increase of about 0.025°C in 2050 and 0.049°C in 2070 assuming a 0.2% increase in fuel consumption at fleet level (Figure 4). These values are computed using AeroMAPS[48], a simplified sectoral integrated assessment model, plugged with the FaIR climate model[49,50]. We further assume that aviation growth follows the IS1 scenario from the LTAG[51]. While CO_2 emissions by aviation strongly depend on the scenario, contrail impact does not as it is mostly proportional to total air distance flown, which is the same for all four scenarios, IS0 (business-as-usual) to IS3 (high ambition). However, as the introduction of SAF as a drop-in fuel is expected to lead to lower contrail forcings, its assumed share can affect the results. The avoided temperature increase thus varies between 0.020°C and 0.027°C in 2050, and between 0.047°C and 0.058°C in 2070, across the scenarios. An alternative interpretation of these results is that **contrail mitigation with 50% effectiveness postpones the aviation-induced temperature increase by on the order of a decade. For instance, under the IS1 LTAG scenario, the temperature increase due to aviation expected in 2048 is only reached in 2061.**

Thus, **contrail avoidance represents a significant lever for reducing the climate impact of aviation. Its potential depends primarily on future levels of air traffic and to a smaller extent on the penetration of alternative fuels**. These results are qualitatively consistent with other published estimates[50,52]. **Nevertheless the temperature benefit from contrail avoidance persists only for as long as contrail avoidance measures are maintained. Further reductions in the climate impact of aviation therefore also require sustained decreases in CO_2 emissions themselves, in addition to non-CO_2 mitigation**[53,54].

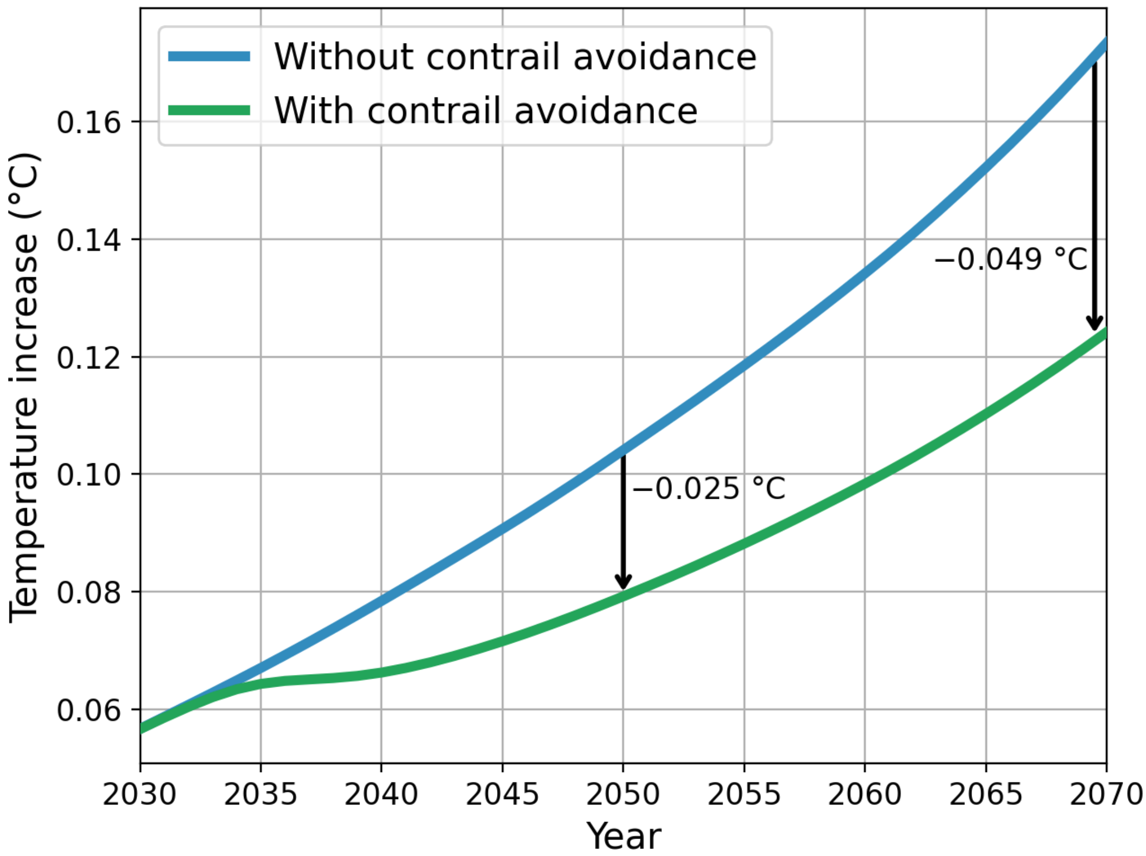


Figure 4. Change in surface temperature due to commercial aviation in scenarios with and without contrail avoidance from year 2030 onwards, assuming the IS1 LTAG scenario for CO_2 emissions.

The avoided temperature increase from contrail avoidance induces a reduction in the fraction of the temperature budget consumed by aviation (Table 3)**.** The total temperature increase in 2025 compared to the pre-industrial era is 1.36°C[55], and the total remaining temperature budget in 2050 is therefore about 0.54°C for the 2°C target, and 0.74°C for an unambitious 3°C target[114]. This reflects the fact that a 2°C scenario requires temperature stabilisation by 2050 while a 3°C scenario exhibits a 2.1°C warming in 2050 before reaching 3°C in 2100. **Implementing contrail avoidance can reduce the fraction of temperature budget consumed by aviation by between 3 and 5 percentage points with respect to the 2°C target**. Overall, the contribution of aviation is reduced by between a third and a half when implementing contrail avoidance, emphasizing the importance of this strategy to reduce the impact of aviation.

	Temperature budget consumed by aviation from 2025 to 2050			
	Towards 2°C in 2100		Towards 3°C in 2100	
Scenario	Without avoidance	With avoidance	Without avoidance	With avoidance
IS0	13% →	8%	9% →	6%
IS1	11% →	7%	8% →	5%
IS2	9% →	5%	7% →	4%
IS3	7% →	4%	5% →	3%

Table 3. Temperature budget consumed by aviation between 2025 and 2050 to reach the 2°C or 3°C target for the four LTAG scenarios, with and without contrail avoidance.

III. The science of contrails

The formation and evolution of aircraft contrails result from a sequence of physical processes acting over a wide range of spatial and temporal scales. These processes are commonly described in terms of four successive phases (also known as regimes, see Table 4). The **jet regime** corresponds to the exhaust flow immediately behind the engine, where hot and moist exhaust gases mix with the ambient air and contrail formation is initiated. This is followed by the **vortex regime**, during which the young contrail is embedded in the aircraft wake and its evolution is governed by the dynamics of the two counter-rotating vortices originating from the wingtips. As the wake decays and eventually disappears, the contrail enters the **diffusion regime**, in which it mixes with the surrounding atmosphere and may spread horizontally and vertically under favourable atmospheric conditions. On longer timescales, **atmospheric adjustments** define how the atmosphere "recovers" from contrail cirrus and influence their overall climate impact.

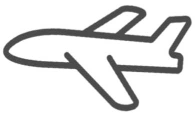
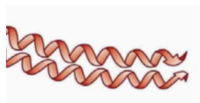
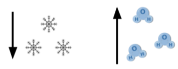
				
Scales	10 s 2 km	100 s 20 km	10 min to hours 100 to 1000 km	hours to days
	The **jet regime** denotes the exhaust flow immediately behind the engine. This is when the contrail forms.	The **vortex regime** denotes the region where the contrail is influenced by the evolving vortices in the wake of the aircraft.	The **diffusion regime** is when the contrail mixes with its surrounding and can spread if conditions are favourable.	**Atmospheric adjustments** can occur on longer timescales associated with the weather systems.

Table 4. Schematic of the different phases of contrail formation and evolution. Each phase (or regime) corresponds to a range of distance and time behind the passing of an aircraft.

Early stages of contrail formation: fuel composition matters

The basic physical principles governing contrail formation are well understood and are described by the Schmidt-Appleman criterion[57,58,59]. In simple terms, this criterion states that a contrail forms when the hot and moist exhaust from an aircraft engine mixes with the cold atmospheric air in such a way that the resulting mixture exceeds some threshold. Small liquid droplets can then form and quickly freeze into ice crystals. As the liquid droplets tend to form around the particles contained in the exhaust plume, both the fuel composition and the engine technology matter for the early stages of contrail formation. Further technical details on the physics of contrail formation are provided in the box below.

Infobox: contrail formation in detail

Contrail formation is governed by the evolution of the aircraft exhaust plume as it cools and mixes with ambient air. The exhaust plume behind the engine is hot and humid and contains a mixture of non-volatile particulate matter (nvPM), such as soot particles emitted by the engine, volatile particulate matter (vPM) formed by condensation of volatile compounds such as sulphuric acid or some organics, internally mixed or coated particles resulting from interactions between these components, as well as ambient particles entrained from the atmosphere in the engine. When the cooling drives the exhaust plume above saturation with respect to liquid water, a large number of water droplets can form, which subsequently freeze into ice crystals. These grow through deposition of water vapour when the plume further dilutes, producing the initial visible contrail in the wake of the aircraft (Figure 5). A few seconds later the exhaust plume enters the two vortices that have formed and grow behind the wingtips. The downward motion of the vortices induces evaporation of the ice crystals in the lower wake, while crystals in the upper wake continue to grow in ice-supersaturated air. After a few minutes, the organised structure of the vortices dissipates and the contrail mixes progressively with the surrounding atmosphere. Contrail formation occurs only when the ambient atmosphere is sufficiently cold and moist to satisfy the Schmidt–Appleman criterion, which defines the thermodynamic threshold for activating the water droplets. Supersaturation of the ambient air with respect to ice is further needed for the contrail to be persistent and evolve into a contrail cirrus.

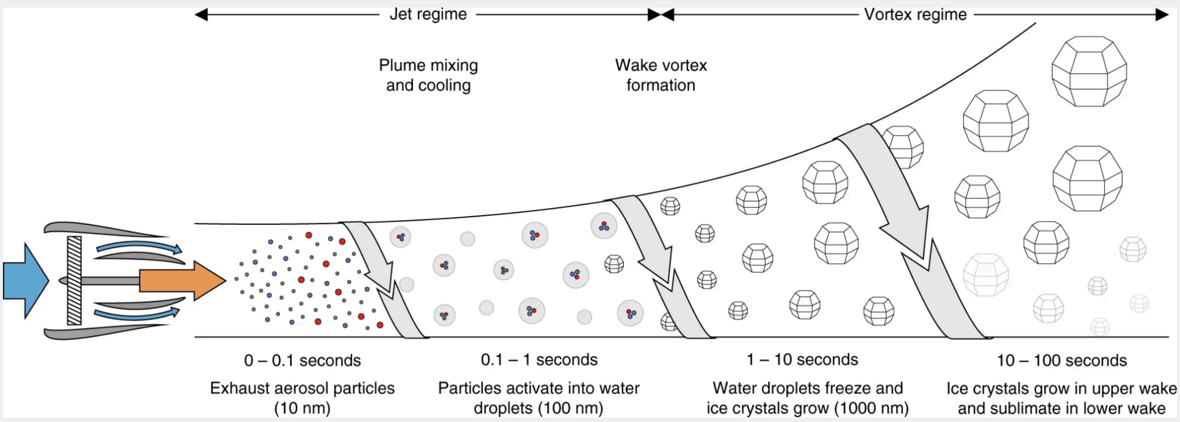


Figure 5. Schematic of the aircraft wake and the processes involved in the contrail formation stage during the jet and vortex regime. From Ref. 60. CC BY 4.0 licence.

Substantial empirical and modelling work shows that fuel composition and engine technology –via their control of particle number, size distribution and chemical composition– influence the properties of freshly formed contrails in terms of ice crystal concentration, size distribution and initial optical depth[60,61]. As the dominant type of particles emitted by an aircraft, soot strongly influences the number of ice crystals that form in contrails. However, when soot emissions are substantially reduced, as can occur with some fuel types or engine technologies, volatile particles (such as sulphuric acid) provide alternative nucleation sites[62] for forming ice, allowing the creation of contrails when suitable temperature and humidity conditions are met. Consequently the sulphur content of the fuel may also influence the contrail ice crystal number[63].

At the same time, a growing body of studies[60,61] highlights that ambient particles (i.e., the particles already present in the atmosphere, irrespective of airplanes) that enter into the plume can participate in droplet activation and ice formation. The ice particle number in an early-stage contrail thus reflects a competition between soot (and other particles emitted during or after the combustion) and ambient particles. This competition likely depends on ambient temperature and humidity, the characteristics of the emitted particles and the ambient aerosol size distribution and chemical composition (Figure 6). In an extreme case such as a hypothetical soot-free hydrogen combustion with very low non volatile and volatile particulate matter (resp. nvPM and vPM) emissions, it is believed that contrail ice can form predominantly on ambient particles[64].

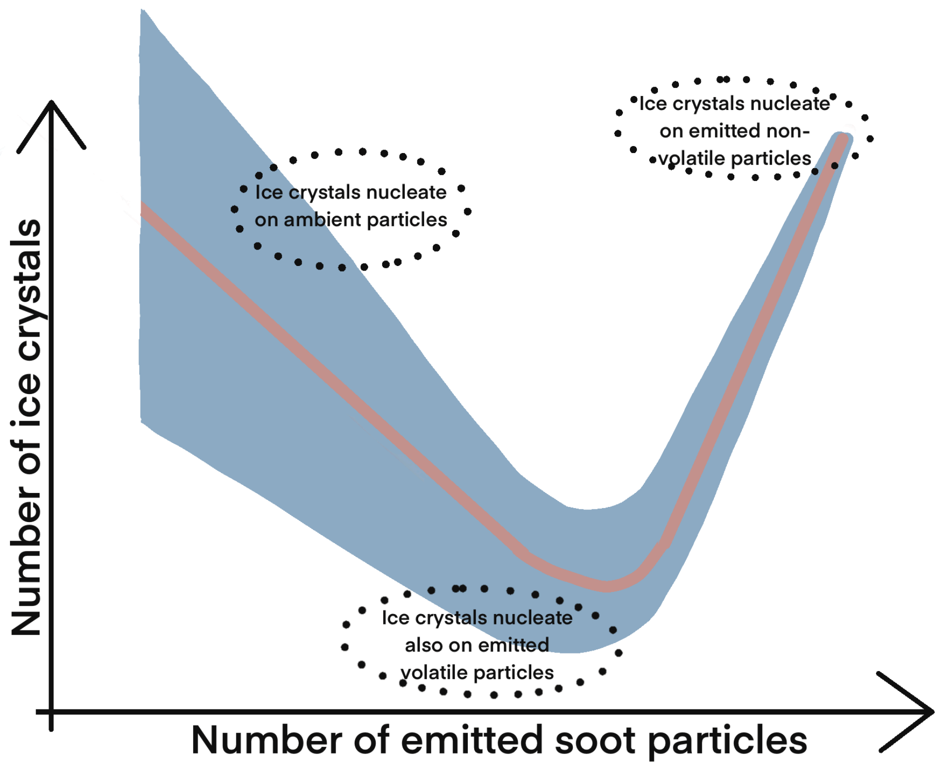


Figure 6. Schematic illustration showing the dependence of contrail ice crystal concentration on the number of (non-volatile) soot particles emitted. The spread is due to diameters of primary soot particles, fuel sulphur content, the number of volatile particles being emitted, and the concentration and size of ambient particles that take over at low numbers of emitted soot particles. A contrail with low initial ice crystal concentration is thought to have less impact on the climate. Adapted from Ref. 61.

The issue of how many and which particles nucleate into ice crystals is not just theoretical as it has clear implications for contrail characteristics and its climate impact. Reductions in soot emission, changes in sulphur content and the use of sustainable aviation fuels (SAF) of hydrogenated kerosene have all been shown to alter nvPM and/or vPM number and therefore the number of activation sites available for droplet formation and subsequent freezing[40,65]. A smaller initial concentration of ice crystals in the contrail modifies the contrail optical properties but, more importantly, few ice crystals tend to be larger and fall quicker in the atmosphere[66,67]. Thus **smaller ice crystal concentrations result in shorter-lasting contrails, which in turn leads to a smaller climate impact.** For instance it was found[66] that a reduction in the initial ice crystal number of 80% leads to a decrease in contrail cirrus radiative forcing by 50%.

Based on these and similar results, **several contrail mitigation strategies have been proposed that consist of substituting kerosene by SAF**[68] **or hydrogenated kerosene**[69]**. As such fuels are more expensive than Jet-A1 and also in limited supply, it has been proposed to make a targeted use of SAF**[69,70] **and hydrogenated kerosene**[71] for flights that are predicted to have a large contrail impact.

It was further suggested that controlled seeding of a small amount of ice-nucleating particles into aircraft exhaust plumes could regulate plume supersaturation by consuming water vapour and limiting peak relative humidity[72]. This study argued that this mechanism could suppress the activation of exhaust particles by up to one to two orders of magnitude, leading to fewer but larger ice crystals. This, in turn, would result in faster sedimentation, shorter contrail lifetimes, and a strongly reduced contrail-cirrus warming effect. This solution would need to be tested as it remains very speculative at this stage.

Important uncertainties remain regarding contrail mitigation strategies that rely on a change of fuel composition, whether or not they are specifically targeting contrail-prone flights. First there is correspondingly less knowledge on emission levels of volatile particles compared to non-volatile particles. Second the degree to which atmospheric particles can substitute for emitted combustion particles under realistic flight conditions is not settled quantitatively: it depends on poorly constrained aspects such as the number and composition of atmospheric particles at flight level, the detailed chemistry and volatility of the emitted particles, and the processes controlling droplet activation and freezing in the rapidly evolving plume. Process studies and simulations of contrail formation show qualitatively consistent results, but observational constraints at cruise altitudes are still sparse and model sensitivities remain large[61]. Engine characteristics (e.g., age and maintenance) as well as the amount of lubricating oil that are burned in the engine emerge as potentially important parameters[73,74]. While it is reasonable to assume that a reduction in soot particle emissions for conventional engines result in a weaker contrail climate impact, the impact of a further decrease in nvPM emissions for lean burn engines is less clear. **Resolving uncertainties on contrail formation processes under soot-poor conditions**

is thus critical to predict how future fleet-level changes in fuels and engines may translate into changes in contrail radiative forcing.

Contrail evolution: from fresh contrails to contrail cirrus

It is equally important to understand the subsequent evolution of contrails after the formation stage because their overall climate impact is determined by the properties of ageing contrails rather than those of younger contrails.

How contrails interact with their surroundings controls their transformation from compact line-shaped features into more diffuse cloud elements. If atmospheric relative humidity with respect to ice remains above saturation, the contrail can evolve into a persistent cloud. Key processes include: (i) deposition of atmospheric water vapour on ice crystals in ice-supersaturated regions, (ii) the downfall of ice crystals, which redistributes them vertically and can thicken the cloud in places, (iii) horizontal spreading of the contrails due to vertical variations in the wind strength, and (iv) mixing with clear sky which can either shrink or broaden the contrail. The large-scale atmospheric dynamics determines the contrail lifetime, often ranging from less than an hour to several hours. **A key question concerns how multiple contrails interact and compete for the available atmospheric water vapour in ice-supersaturated regions.** It is anticipated that, under conditions of dense air traffic, contrail climate impact may exhibit saturation behaviour, with additional contrails having less impact. Consequently, avoiding contrails from a subset of aircraft may deliver less climate benefit than expected if other aircraft produce contrails within the same air mass. This may have implications for contrail avoidance strategies that are not yet fully explored.

The extent to which ISSRs (atmospheric regions prone to contrail formation) overlap with cirrus clouds is another area for further investigation. Indeed cirrus clouds often exist in air that can be either dry (leading ice crystals to shrink) or moist (allowing them to grow), conditions referred to as undersaturation and oversaturation with respect to ice[75]. However there are few simultaneous measurements of humidity, ice crystal concentrations, and ice water content. The climate effects of contrails embedded in cirrus clouds is an emerging issue but it is not clear yet what it means for the assessment of the climate impact of contrails and contrail cirrus. It was reported that a large majority of ISSRs occurs inside cirrus clouds[76]; however this may correspond to cases of very thin cirrus clouds with limited climate impact. Other studies showed that there is a systematic increase in cirrus cloud optical depth inside mid-latitude flight tracks compared with adjacent areas outside the tracks[77] or with the COVID-19 period with less traffic[78]. Contrails embedded into cirrus clouds are expected to enhance the warming effect from these cirrus clouds. It was further shown that embedded contrails represent a small contributor to aviation's impact on climate[79]. However it is not yet clear whether embedded contrails are responsible for an additional radiative forcing relative to previous estimates, or whether they somewhat reduce past estimates because the fraction of contrails occurring in cirrus clouds was underestimated.

Radiative impacts: an established theory but some implementation challenges

Contrail cirrus interact with the Earth's radiation budget by reflecting a small fraction of incoming solar radiation and by absorbing, scattering, and emitting terrestrial radiation as shown on Figure 7. A smaller amount of terrestrial radiation is emitted towards space in the presence of contrail cirrus because the radiation escaping to space is emitted at a lower temperature than would have been the case otherwise. These cooling (in the solar spectrum) and warming (in the terrestrial spectrum) effects partly offset each other, with the net impact depending on cloud properties and environmental conditions. Radiative forcing (RF) is defined as the change in radiative flux (typically evaluated at the top of the atmosphere) between atmospheres with and without contrail cirrus, and depends on factors such as contrail optical depth, ice crystal size and number, contrail altitude and temperature, as well as environmental conditions (temperature and humidity profiles, cloud vertical structure, surface properties).

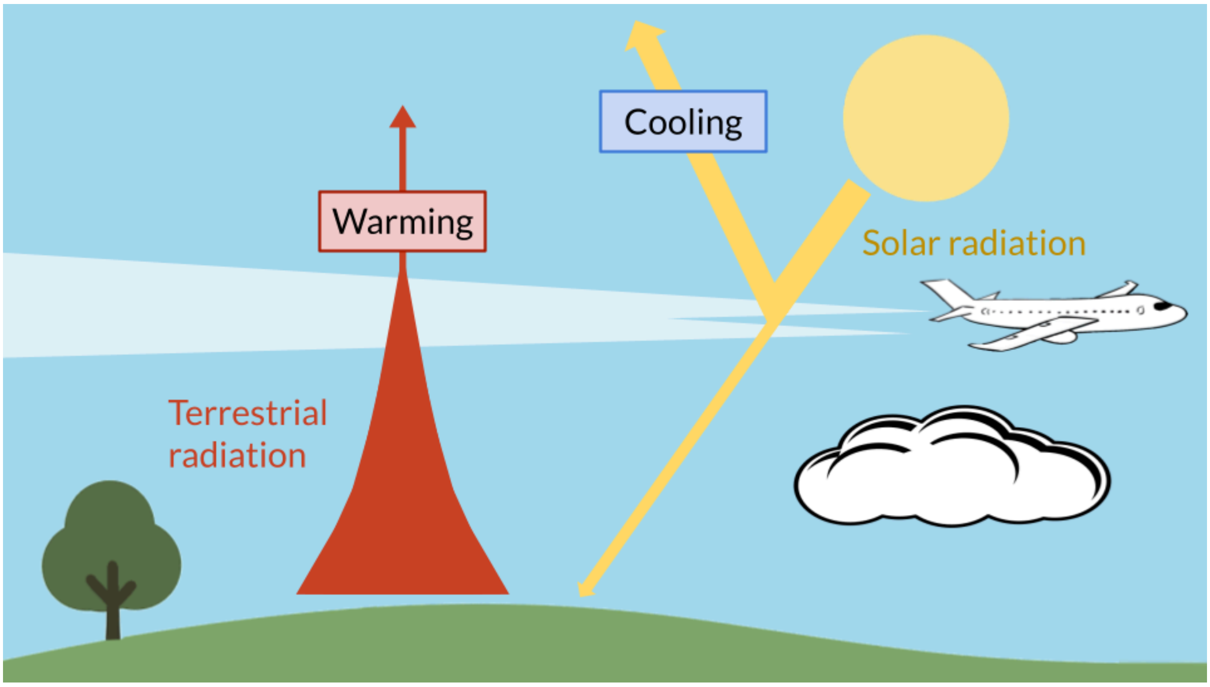


Figure 7. Schematic of the radiative impact by contrail and contrail cirrus. They interact both with solar radiation (during daytime) and terrestrial radiation emitted by the Earth's surface and the atmosphere (during both daytime and nighttime). The radiative impact by contrail and contrail cirrus depends also on their environment, e.g. the presence of other clouds.

The radiative impact from contrails and contrail cirrus can be assessed from calculations based on the radiative transfer theory and from observations of radiative quantities themselves using sensors placed at the Earth's surface and on satellites.

Detailed radiative transfer calculations have been performed and document the parameter space that produces positive or negative radiative forcing in terms of microphysical and macrophysical contrail properties and environmental conditions[80,81]. However, fully representing the complexity of contrails and their coupling to the surrounding atmosphere remains challenging, in particular their interaction with other clouds and variable surface conditions. There are subtle aspects to consider when performing radiative transfer calculations for contrails. Contrails and contrail cirrus are often considered to consist of large and homogeneous layers. However cloud inhomogeneities and cloud edges have an impact on the radiative transfer. These effects, due to the three-dimensional structure of contrails and cirrus clouds, have been shown to be non-negligible in some situations[82,83,84]. Nevertheless, these effects are often neglected in contrail studies relying on climate models or on simplified models. For instance the threshold contrail optical depth at which the contrail forcing changes sign (from warming to cooling) occurs depends not only on the position of the Sun in the sky but also the cloud geometry. As a result, **calculations that combine all the elements required for a benchmark radiative transfer dataset, namely line-by-line spectral accuracy, a realistic representation of the contrail environment, and three-dimensional radiative effects are still required.** This represents a challenging, but feasible, endeavour given current modelling capabilities. Since radiative quantities are also well observed both at the Earth's surface and from space, **this knowledge gap could also be addressed by developing reference observational datasets of the radiative impact of contrail cirrus.**

The concept of energy forcing[19], defined as the accumulation of the radiative forcing over the lifetime of contrail cirrus, is particularly convenient for assessing the overall radiative impact of a contrail event. This metric is appealing because it directly quantifies the net energy added to the Earth system, expressed in physical units (petajoules). By applying this framework to large-scale contrail outbreaks that developed under clear-sky conditions over Western Europe in June 2020 (see figure 8), it was shown that the estimated energy forcing could be sensitive to the timing and length of the contrail outbreak[11]. Furthermore it may be difficult to objectively determine the termination of a contrail outbreak.

An important consideration is that, for contrail cirrus and contrail outbreaks occurring predominantly at night, uncertainties in radiative forcing and energy forcing are reduced to uncertainties in the terrestrial component alone, since the compensating solar effects are absent (see figure 7). **As a result, in nighttime conditions, estimating both the magnitude and the uncertainty structure of the contrail forcing is substantially simpler than in daytime conditions, when partial compensation between solar and terrestrial radiative effects occurs.**

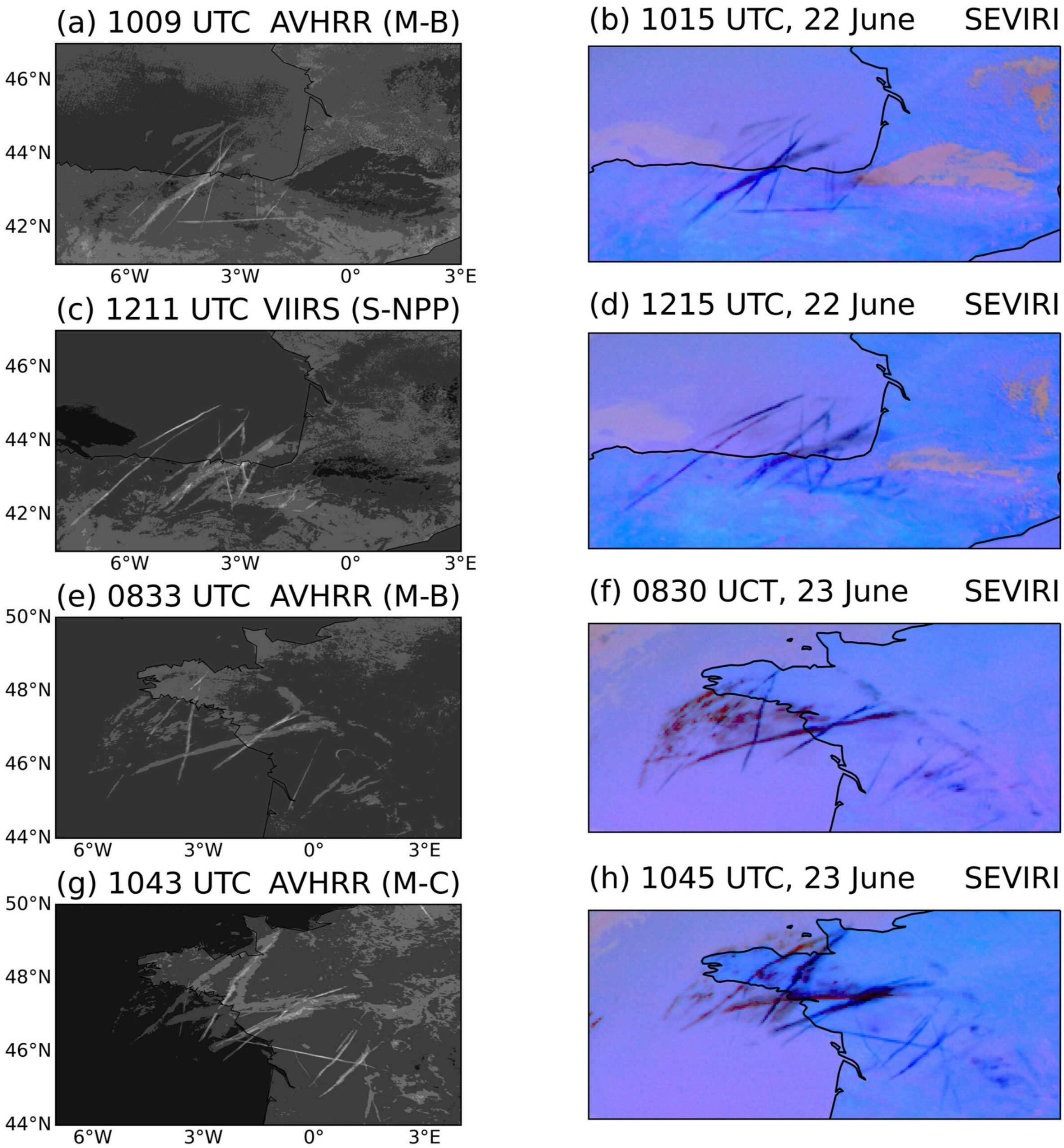


Figure 8. Example of a contrail outbreak monitored by polar-orbiting (left) and geostationary (right) satellite imagery. On the right panels, the dark blue colors indicate high and thin cirrus with no clouds below, while dark brown illustrates high thick ice clouds. From Ref. 11.

Atmospheric adjustments: a critical knowledge gap

A key question is to what extent contrail-induced ice formation depletes humidity in a way that suppresses, delays, or replaces the development of natural cirrus clouds. An important consideration to assess the climate impact of a contrail outbreak is indeed to define the counterfactual situation, namely what the atmospheric state would have been in the absence of contrail cirrus. The counterfactual situation cannot be simply "created" by removing the contrail cirrus from a satellite image or a model simulation because contrail cirrus can significantly reduce natural cirrus cloudiness by redistributing and depleting water vapour in the upper troposphere[85]. The processes involved are termed atmospheric adjustments because the atmosphere adjusts itself to the presence of these contrail outbreaks. **Atmospheric adjustments, in particular through changes in humidity and natural cloud cover in the vicinity of contrails, are expected to partly offset the warming effect of contrail cirrus.** In other words, contrails and contrail cirrus increase artificially the greenhouse effect but atmospheric adjustments tend to decrease the natural greenhouse effect. There is also high confidence that such adjustments are non-negligible in the overall climate response.

Atmospheric adjustments to contrail cirrus can be framed in terms of two fundamental, competing processes triggered by contrail formation[86] as shown on Figure 9. The first is a relatively rapid dehydration of the upper troposphere, as ice crystals formed in contrail cirrus grow and sediment, removing water vapour from the layer in which the contrail developed. The second is the replenishment of upper-tropospheric water vapour through atmospheric motions, which operates intermittently and potentially on longer timescales. The strength of the resulting adjustment depends on the relative timing and efficiency of these processes: when sedimentation-driven dehydration dominates, adjustments can substantially offset contrail-induced radiative forcing, whereas efficient and rapid moisture replenishment tends to weaken the adjustments.

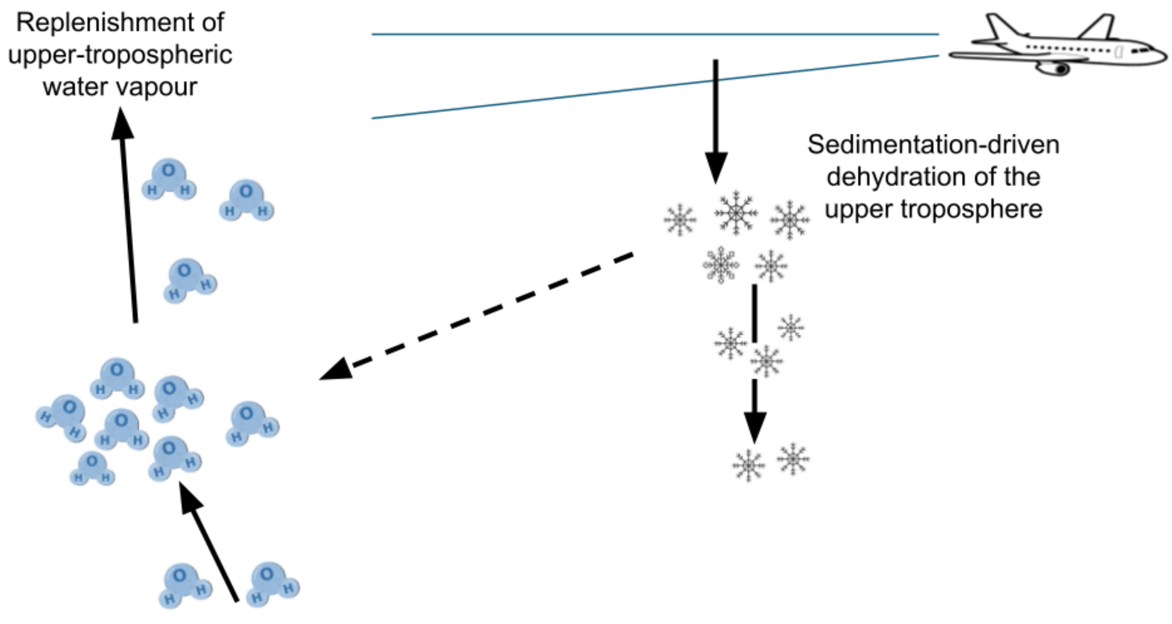


Figure 9. Schematic of the two competing processes triggered by contrail formation controlling the strength of atmospheric adjustments and their contribution to the effective radiative forcing.

Atmospheric adjustments therefore play a central role in distinguishing the concepts of radiative forcing from effective radiative forcing. The former characterizes the radiative impact of the contrail cirrus taken in isolation whereas the latter is defined as the sum of the radiative impact due to both the contrail cirrus and the subsequent rapid adjustments of the atmosphere. **This distinction is important because effective radiative forcing (ERF) more faithfully captures the net energy perturbation experienced by the climate system and is consequently a better predictor of the eventual surface temperature response than the radiative forcing (RF) alone.**

Climate efficacy describes the ability of a given climate forcing mechanism, such as that of contrail, to change global temperature compared to CO_2, for the same amount of radiative forcing. Formally, the climate efficacy of a forcing agent is defined as the ratio of the global mean temperature response it produces to the temperature response caused by CO_2 assuming equal radiative forcing. An efficacy of 1 means the forcing is just as effective as CO_2 at warming the climate. Values below 1 indicate a weaker temperature response per unit forcing. This concept is important because we aim to convert the climate impact of contrails into some sort of CO_2 equivalence.

The climate efficacy of contrails relative to CO_2 can be defined using either RF or ERF. By construction, the efficacy based on ERF is expected to be closer to unity than that based on RF, since ERF accounts for rapid atmospheric adjustments. However, the literature remains sparse, and reported values of contrail efficacy are sometimes ambiguous as to whether they are derived from RF or ERF. **Available evidence suggests that, even when defined in terms of ERF, the climate efficacy of contrails is likely significantly below unity**[46] despite capturing most if not all of the atmospheric adjustments. This may be due to the localised vertical origin of the contrail cirrus radiative perturbations which reduces their ability to translate an effective radiative forcing into a temperature response in comparison to well-mixed greenhouse gases such as CO_2.

Contrail efficacy therefore needs to be taken into account when comparing the climate impact of contrails with that of CO_2. In practice, this is commonly achieved by converting contrail effective radiative forcing into a CO_2-equivalent metric using the effective global warming potential over 100 years (EGWP100), that is, the 100-year GWP of contrails weighted by their climate efficacy. Further discussion of climate metrics and their implications for comparing contrails and CO_2 is provided below.

In conclusion, it is important that future research addresses the question of atmospheric adjustments associated with contrail cirrus in climate models in order to increase confidence in estimates of the surface temperature change due to contrails. One research avenue is to seek observational constraints for the associated processes. A key open question, and an important source of uncertainty, is whether atmospheric adjustments to contrail cirrus depend on the prevailing weather situation. Variations in the relative strength and timing of dehydration and moisture replenishment processes may cause the magnitude of adjustments to evolve in time for a given air mass. Such variability could, in turn, alter the ranking of regions and meteorological situations in which contrail avoidance would be most effective.

Observing contrails: towards data-driven approaches

Humidity in ice supersaturated regions, contrails and contrail cirrus can be observed using a range of complementary observing systems, including ground-based, in situ, and satellite instruments. Ground-based observations rely on instruments such as sky cameras, lidars, and radiometers, which provide detailed information on contrail occurrence and optical properties. Sky cameras are helpful to detect contrails in clear-sky conditions; lidars[87] can detect the height and density of drifting contrails by emitting rapid laser pulses and measuring the time it takes for the backscattered light to return to the sensor; radiometers measure solar and terrestrial radiative fluxes reaching the surface and how they are influenced by contrails and cirrus. In situ observations are obtained primarily from meteorological radiosondes[88] and balloons, research aircraft and to some extent commercial aircraft through the IAGOS programme[89], deliver highly accurate measurements of temperature, humidity, and aerosol and ice particle properties, which are critical for constraining contrail formation and evolution. Satellite observations from both geostationary and polar-orbiting platforms employ a variety of sensors, including imagers, lidars, and microwave radiometers, enabling regional to global monitoring of contrail occurrence and persistence.

These observational approaches differ substantially in their spatial and temporal sampling, resolution, and measurement accuracy. They should therefore be seen as highly complementary and there is significant value in exploiting them synergistically to better constrain contrail processes across different scales. Geostationary satellites offer high temporal resolution and are particularly well suited for analysing contrail outbreaks and their temporal evolution[11]. However, their spatial resolution (especially at high latitudes) remains insufficient to detect many individual contrails, especially in their younger stage, limiting their ability to provide comprehensive contrail statistics on their own[90,91,92]. Recent work has shown how they can be used to quantify the ERF by contrail in independent ways[93].

Overall, existing contrail detection algorithms generally perform well under favourable observing conditions. However, important challenges remain, due to the limited spatial resolution of some instruments and the presence of background cloudiness that can mask contrails (particularly for ground-based observations), which complicates the attribution of detected contrails to individual flights. These limitations highlight the value of combining different sources of information (e.g. ground-based cameras with satellite imagery, high-resolution but infrequent low-orbit satellite imagers and low-resolution but frequent geostationary satellite imagers). Well-documented contrail and contrail-cirrus datasets are being available in the public domain, which supports the development and intercomparison of detection algorithms and facilitates independent evaluation.

The science of contrail observation is advancing rapidly. This provides increasingly more confidence on the quantification of contrail occurrence and their radiative impacts and paves the way towards data-driven models. At the same time, contrail observations will remain inherently imperfect, owing to limitations in coverage, resolution, and detectability. As a result, the quantification of contrail impacts will continue to rely partly on modelling and statistical approaches, even as observational capabilities improve**. Thus, policy action should not wait for a perfect verification tool, but instead focus on building sufficient confidence in existing observations and models to enable a statistically robust quantification of climate benefits.**

Also it should be noted that atmospheric adjustments are not easy to observe and constrain. Likewise the impacts of contrail cirrus on surface temperature are not measurable.

Contrail modelling: in need of intercomparison

Different classes of models are employed to simulate contrails at successive stages of their life cycle (see Table 4). At the formation stage, detailed plume models are required to explicitly represent the effects of fuel composition and engine combustion on the number of particles in the plume and the initial contrail properties of contrails such as the number of ice crystals. Complex models that can simulate the coupling between dynamical and microphysical processes are also necessary to simulate the early contrail evolution in the vortex regime. For contrail avoidance applications, the most relevant models are those capable of simulating the contrail evolution from minutes to several hours after formation. Finally, regional and global atmospheric models are used to simulate how contrails interact with the atmosphere on timescales of up to a few days, which is the typical timescale for atmospheric adjustments. These last two classes of models need to be coupled to a radiative transfer model to compute the radiative perturbations due to contrails.

There is a trade off between model complexity and physical realism and model computational efficiency. This trade-off is particularly evident when comparing highly parametrised approaches such as algorithmic climate change functions (aCCF)[94], reduced-complexity Lagrangian models such as the contrail cirrus prediction model (CoCiP)[95] and detailed plume-scale models such as the Aircraft Plume Chemistry, Emissions, and Microphysics Model (APCEMM)[96]. The choice between these modelling approaches therefore depends on the scientific or operational objective: process understanding and parameterisation development favour high-fidelity models such as APCEMM, whereas large-scale impact assessment and trajectory optimisation require more computationally efficient models such as CoCiP. The aCCF are useful for assessing fleet-wide scenarios but are too simplified for operational implementation of contrail avoidance strategies. Parameter perturbation approaches can be used to sample uncertainties[97]. **Data-driven models offer a promising pathway to partially reconcile physical realism and computational efficiency.** By learning statistical relationships from high-fidelity simulations (e.g. APCEMM, large-eddy simulations) or from observational datasets, machine-learning models can emulate complex processes at a fraction of the computational cost.

There have been few comparisons of contrail models against observations or against one another. A comparison between CoCiP and APCEMM has shown that sedimentation of ice crystals in the two models to be different, leading to differences in contrail lifetime and optical depth[98]. CoCiP should also be compared to actual observations made during contrails outbreaks to assess the quality of the model outputs[11]. **As model capabilities expand, structured model intercomparison efforts will provide an effective framework for robust model evaluation[99].** Such model intercomparisons should prioritize (i) variables directly relevant to contrail avoidance (e.g., radiative or energy forcing), (ii) quantities that are at least partially observable, and (iii) atmospheric situations of operational significance for contrail mitigation (i.e., persistent contrails and large-scale contrail outbreaks).

It should not be expected contrail models, whether they are physically-based or data-driven, to simulate every contrail situation to a high accuracy. It is more important initially that contrail models make unbiased predictions of contrail energy forcing, especially for the most impacting contrail situations, so that contrail avoidance strategies are well calibrated and deliver climate benefits on average. It is also important that contrail models represent contrail–contrail interactions (i.e. the extent to which two individual contrails compete for atmospheric water vapour and interact with one another). The higher the performance of contrail models, the better, as this will help to target the most appropriate contrail situations and increase the efficiency of contrail avoidance strategies.

Surface warming pattern due to contrails

Most research on the climate effects of contrails and induced cirrus has concentrated on estimating their RF or ERF, yet **the ultimate objective of contrail avoidance strategies is to reduce their climate impacts, particularly in terms of surface temperature change.** Thus it is important to estimate the climate response to contrails. The spatial pattern of surface temperature response is not expected to correspond directly to that of the RF and ERF, and to date there exists no established mapping between regional contrail RF and regional surface temperature change. Only two studies have investigated the pattern of the surface temperature response to the contrail perturbation[38,44]. The two studies report an inhomogeneous response with consistent warming hotspots over the continents of the Northern Hemisphere (see Figure 10). This underscores the complexity and the current uncertainty in quantifying contrail-driven climate impacts as well as the need for further climate simulations to confirm the findings. It should be noted that the surface warming pattern due to contrail cirrus can only be inferred though climate simulations and cannot be detected in the observed climate records. Indeed it represents a small perturbation compared to natural variations and other anthropogenic perturbations in the climate system.

In conclusion, **surface warming due to contrails cannot be detected in climate**

records but a small number of model simulations suggest that it occurs disproportionately over continents.

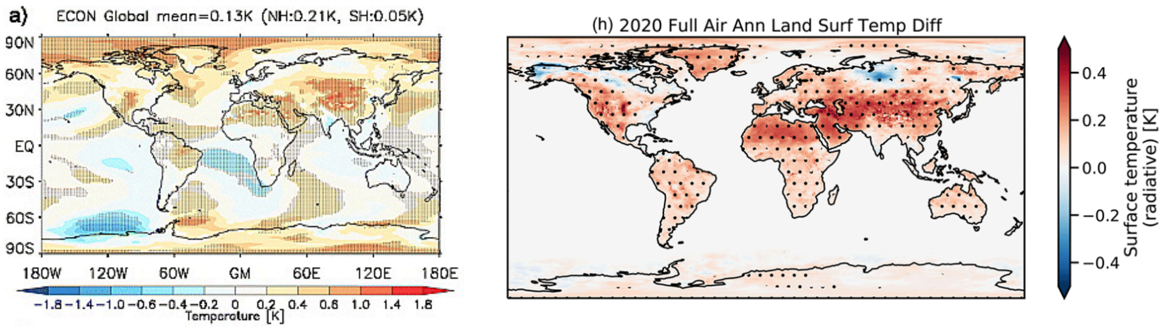


Figure 10. Patterns of surface warming due to contrails. Left panel is from Ref. 44 (© AGU with permission). Right panel is from Ref. 38 (CC-BY-4.0 licence). The magnitude of the contrail perturbations have been inflated in model simulations to better simulate and detect the warming pattern.

Recommendations for contrail science

The preceding section has reviewed the current understanding of the physical processes governing the lifecycle of contrail and their climate impacts, as well as remaining uncertainties. These insights provide a basis for identifying priority areas where targeted efforts could most effectively advance contrail science. The following recommendations summarise key directions for future research.

Recommendation #1 - Focus on the uncertainties that matter
Future observational studies should be targeted specifically to address key sources of uncertainties that matter for quantifying the climate impact of contrails and contrail mitigation strategies (e.g., ice crystal concentration and size, contrail environment, contrail radiative impact).

Recommendation #2 - Conduct more flight tests to study alternative fuels
Further targeted field campaigns, including dedicated flight tests, are required to advance our understanding of ice nucleation during initial contrail formation for alternative fuels (SAF and hydrogenated kerosene), across multiple engine technologies and representative meteorological and background aerosol conditions.

Recommendation #3 - Encourage open-access contrail datasets
It is recommended to establish a coordinated framework for contrail observations that systematically expands existing open-access datasets from ground-based cameras and satellite sensors to include co-located spaceborne lidar–radiometer measurements, high-resolution imagery from Sentinel- and Landsat-type platforms, and contrail outbreak scenes captured by geostationary imagers; such harmonized

datasets would enable rigorous evaluation of contrail impact models and support the development of robust data-driven approaches.

Recommendation #4 - Intercompare contrail process models
Given that a small but expanding set of contrail process models now exists, it is timely for the community to initiate structured model intercomparison projects, guided by clearly defined objectives and a common experimental protocol. When possible, the protocol should be anchored to observational cases to ensure meaningful and robust evaluation. Such an intercomparison project will help to quantify the robustness in contrail radiative impacts under different meteorological conditions.

Recommendation #5 - Bridge radiative transfer calculations and observations
Benchmark radiative transfer calculations are needed that explicitly account for contrail spatial inhomogeneities, three-dimensional effects and the interactions of the contrail with its environment. Such benchmark calculations should be confronted with observations quantifying how contrails perturb the Earth's radiative budget.

Recommendation #6 - Resolve radiative forcing-temperature relationship
a) It is recommended to strengthen efforts to quantify atmospheric adjustments associated with contrails and how they may vary regionally and/or depend on the background meteorological conditions. Such research could adopt a synergistic approach combining high-resolution limited-area models (such as used for numerical weather prediction), global climate models, and satellite observations.
b) Quantifying and narrowing the uncertainty in the climate efficacy of the effective radiative forcing by contrail cirrus would benefit from coordinated climate model experiments. Such an effort would help identify both commonalities and differences in climate model responses to contrail cirrus. Such an intercomparison could take place under the auspices of the Climate Model Intercomparison Project (CMIP) of the World Climate Research Programme (WCRP).

IV. Building trust in contrail mitigation

Critical uncertainties for contrail avoidance and management

A range of contrail mitigation strategies has been proposed, which can be broadly classified into contrail avoidance schemes and contrail management schemes. These strategies are further sub-categorised in Figure 11, and five specific approaches are examined in this report.

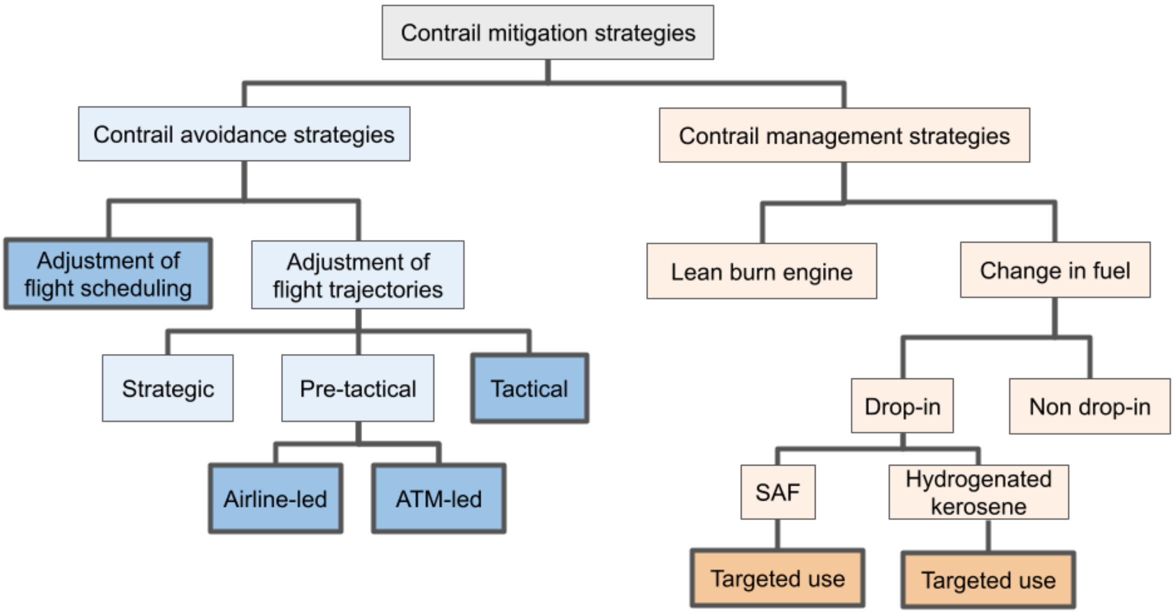


Figure 11. Different contrail mitigation strategies categorised as contrail avoidance strategies (in blue) and contrail management strategies (in orange). The potential, effectiveness and uncertainty level of the different strategies vary substantially. The five strategies examined in this report are highlighted with darker colours.

A first approach acts at the flight-scheduling stage (i.e. typically 6- to 12-month ahead), relying on climatological estimates of contrail-induced warming to optimise the network design. Weather forecasts lose predictive utility beyond a week or two, but climatological averages of atmospheric conditions can be used to assess the likelihood of contrail formation and their potential warming impact for different pairs of origin and destination airports. It is then possible to adapt, at least to some extent, the time of departure (e.g., morning, afternoon, or night) and the choice of aircraft according to their ceiling height, in order to minimise the risk of forming warming contrails.

A second approach operates during the strategic planning of a flight (i.e. pre-tactical phase, taking place typically two to six hours ahead of a flight) using actual weather forecasts to avoid contrail-prone regions. Contrail avoidance can be implemented on a flight-by-flight basis, with responsibility resting primarily on individual airlines, or collectively for all flights traversing a given airspace, with responsibility assigned to air traffic management. **This differentiates airline-led from**

ATM-led contrail avoidance strategies through pre-tactical flight rerouting, although the active role of air traffic control is required for both.

A third option is in-flight rerouting (tactical phase), guided by real-time information on ice-supersaturated or contrail-forming regions. This strategy requires observations of atmospheric conditions available in real time, the capability for predicting the weather on a very short time horizon (i.e. nowcasting), and close cooperation between airlines and air traffic control.

Beyond trajectory-based measures, fuel-based contrail management strategies (e.g. modification of fuel properties or SAF blends) offer an additional lever. As discussed above, lower emissions of soot particles likely result in less warming contrails though uncertainties remain important. Since the supply of SAF will remain limited in the coming years and decades, it may be appropriate to favour the use of SAF for contrail-forming flights (i.e. targeted use of SAF for contrail mitigation).

Each of these approaches has its own advantages and limitations (see annex for a SWOT analysis). In particular their potential and practical implementation feasibility may vary considerably. For instance, shifting nighttime flights to daytime may be feasible in some cases but would probably result in prohibitive costs for many airline network designs.

As noted in previous assessments[100], **effective contrail mitigation will likely require a combination of complementary approaches**. Hybrid strategies may also be relevant. For example, a collaborative decision-making framework involving both airlines and ATM may be more appropriate than considering airline-led and ATM-led strategies as distinct categories.

We further consider four key areas of uncertainties due to imperfect knowledge of contrails. These four key areas correspond to different processes and timescales but overlap to some extent: the first one relates to how the **properties of fresh contrails** influence their lifecycle, the second one concerns the estimation of the **radiative impact of contrails** in their environment, the third one is about **how contrails interact among themselves** on short timescales and compete for atmospheric water vapour, and the fourth one focuses on **atmospheric adjustments and climate efficacy**.

We then project the key area of uncertainties onto the five contrail mitigation strategies using a four-level rating scale as shown in Table 5a. This scale reflects how critical it is to reduce each uncertainty prior to the operational implementation of a given strategy as illustrated in Table 5b. The assessment includes some level of expert judgement and is primarily intended as a tool to prioritise research needs for operationalisation and should not be viewed as a barrier to move towards deployment, especially for strategies with the lower uncertainty levels. Table 5b can be read column-wise to assess the scientific maturity of each strategy, and row-wise to identify whether a given area of uncertainties affects only a subset or the majority of strategies.

Level 0. A key area of uncertainties labelled "green" has a minimum impact on the effectiveness of a contrail avoidance strategy. It may be irrelevant or the uncertainties are expected to average out across situations without reducing the effectiveness of the strategy.

Level 1. A key area of uncertainties labelled "white-green" has a small impact on the effectiveness of a contrail avoidance strategy. Uncertainties can be constrained through observations or are expected to average out across situations.

Level 2. A key area of uncertainties labelled "yellow-green" may result in targeting the wrong situations, with a potential impact on the effectiveness of a contrail avoidance strategy. Ongoing and future contrail avoidance trials and studies are expected to reduce the uncertainties.

Level 3. A key area of uncertainties labelled "yellow-black" may result in targeting the wrong situations or reduce the overall effectiveness of a contrail avoidance strategy. Fundamental research and large-scale contrail avoidance trials are needed to reduce the uncertainties.

Table 5a. Schematic representation of the four-level rating scale and its interpretation. An uncertainty level is applied to each combination of a key area of uncertainties and a contrail avoidance strategy in Table 5b.

The first area of uncertainty concerns the microphysical properties of fresh contrails, i.e. the initial physical characteristics of the ice particles that make up the contrail, because such properties influence the later stages of the contrail lifecycle and its radiative impact. **This area of uncertainties is most important for the contrail mitigation strategy relying on the use of alternative fuels in lean-burn engines.** As discussed previously and in an ANCEN background note[101], a moderate decrease in particle emissions has the potential to lower contrail-cirrus related climate impacts. This suggests that alternative fuels (such as SAF and hydrogenated kerosene) bring a positive climate benefit for conventional, rich-burn engines (uncertainty level 1). However such alternative fuels may result in complex effects for the low emission rates of lean-burn engines as nvPM can serve to form more numerous ice crystals, with relatively few observations to date to back up the theory (uncertainty level 3). For contrail avoidance strategies, this area of uncertainties is in part mitigated by a relatively large body of observations that are used to validate and calibrate models of contrails and their radiative impact (uncertainty level 1).

Radiative impact calculations represent another area of uncertainties. They arise either from the radiative transfer schemes themselves or from their input parameters characterising the contrail and its environment. These uncertainties need to be reduced because the partial compensation between solar and terrestrial effects mean that small errors on one or the other component result in a larger error on the combined impact. However **this area of uncertainties is much less relevant when contrail cirrus predominantly persist during nighttime, as is the case in the polar night or for evening flights**. Thus this area of uncertainties is rated at level 1 for contrail avoidance strategies focused on nighttime conditions and level 2 for contrail avoidance strategies that would also target daytime conditions.

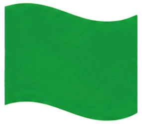
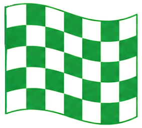
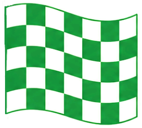
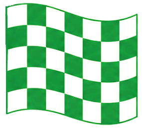
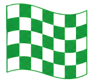
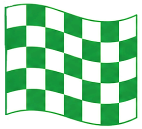
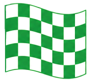
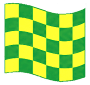
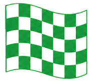
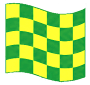
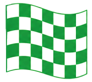
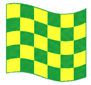
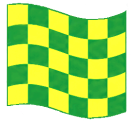
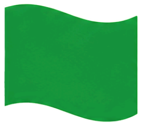
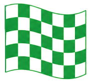
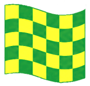
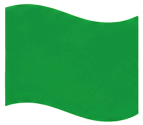
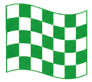
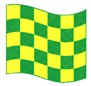
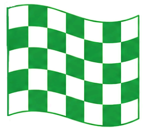
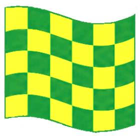
Strategy / Potential / Source of uncertainties	Contrail avoidance through flight scheduling	Contrail avoidance through pre-tactical flight rerouting		Contrail avoidance through tactical flight rerouting	Contrail management through targeted SAF use
		Airline-led	ATM-led		
	Low-medium potential	Medium-high potential	High potential	Unknown potential	Unknown potential
Contrail microphysical properties in fresh contrails and implications for contrail lifecycle					 Rich-burn engine  Lean-burn engine
Radiative impact calculations (incl. knowledge of contrail environment)		 Nighttime  Daytime	 Nighttime  Daytime	 Nighttime  Daytime	
Contrail – contrail interactions and competition for ambient water vapour		 Low traffic  High traffic		 Low traffic  High traffic	
Atmospheric adjustments and climate efficacy					

Table 5b. Assessment (through expert judgement) of the importance of four key areas of uncertainties across a selection of five contrail mitigation strategies. The rating scale (green, white-green, yellow-green, yellow-black) indicates how critical it is to reduce the uncertainty before operationalisation of a given contrail mitigation strategy (Table 5a)

Contrail-contrail interactions represent a key area of uncertainties that is rated at levels 1-2 for airline-led contrail avoidance depending on the air traffic density, **but level 0 for the ATM-led approach**. Indeed it is envisaged that ATM-led mitigation would typically rely on a more systematic avoidance of atmospheric regions that are prone to contrail cirrus formation with temporary airspace closure, making it closer to an all-or-nothing strategy than airline-led avoidance. In practice, hybrid approaches where the impact is minimized without airspace closures may offer a more operationally feasible compromise, combining targeted rerouting with strategic flow management. Tactical rerouting is rated at levels 1-2, depending on factors such as air traffic density, the size of the region to be avoided, and the available airspace capacity, similarly to pre-tactical airline-led contrail avoidance.

The magnitude of atmospheric adjustments in response to contrail cirrus formation is identified as a key area of uncertainties that is largely independent of the mitigation strategy considered (levels 2-3). If such adjustments offset a substantial fraction of the contrail radiative forcing or if adjustments depend on the meteorological situations in an unknown way, the effectiveness of contrail avoidance strategies would be reduced. Understanding better atmospheric adjustments should therefore be a research priority. **It should be noted however that the uncertainty on rapid adjustments does not invalidate the concept of contrail avoidance.** Given the wide range of radiative effects observed at the scale of individual contrails, stronger negative rapid adjustments would reduce the number of cases in which avoidance yields a net climate benefit, but would not eliminate them. Situations in which contrails exert a substantial positive radiative forcing would still justify targeted avoidance strategies.

Among the different strategies, contrail avoidance through flight scheduling is implemented on a climatological basis. It would typically consist in **scheduling more flights during daytime and fewer flights during nighttime to enhance the offsetting of the contrail greenhouse effect** by the contrail albedo effect. Such a strategy therefore aims to achieve benefits on average and is more robust to situation-dependent uncertainties. Its main drawback, however, is likely to be a more limited mitigation potential.

Contrail avoidance implemented at the pre-tactical and tactical stages exhibits differing levels of maturity, depending on the mode of implementation. In particular, contrail-contrail interactions become much less critical in low-traffic regions. Uncertainties associated with radiative transfer are also of reduced importance for contrail cirrus persisting predominantly during nighttime, with only limited extension into the subsequent daytime period, although uncertainties in contrail cirrus lifetime remain relevant in such cases. These considerations suggest that **airline-led contrail avoidance is a very promising initial pathway if focused on low-traffic regions and predominantly nighttime operations, while ATM-led contrail avoidance could likewise initially prioritise nighttime periods.** Assessing the fraction of climatically impactful contrail cirrus covered by these conditions would be a valuable next step.

Finally it should be noted that uncertainties arise at every stage of the process chain from contrail formation to the climate impact. While a bottom-up propagation of process-level uncertainties would suggest a large overall uncertainty, observational constraints at key stages of this chain substantially reduce the effective uncertainty in the resulting climate impact estimates.

Learning from past contrail avoidance trials

There has been a small number of contrail avoidance trials in the past few years. Table 6 lists past, ongoing and upcoming trials that have resulted or are expected to result in scientific analyses. We discuss below their main characteristics and lessons learned from them. There have also been a few other independent contrail avoidance trials; however these are undocumented in the scientific literature, which limits their usefulness.

Past contrail avoidance trials vary significantly in terms of experimental design and level of reporting detail. This diversity complicates cross-comparison and synthesis of results. There are essentially four contrail avoidance trials that have published a synthesis of their results:

- an ATM-led trial over the Maastricht Upper Area Control area in 2021, with support from the DLR and Eurocontrol[24];
- an airline-led trial conducted by American Airlines with support from contrails.org, Flightkeys and Google[31] between January and June 2023;
- an airline-led trial conducted by TUIfly as part of the 100-flights-trial[33,102], with support from the DLR in September 2024;
- an airline-led trial conducted by American Airlines with support from contrails.org, Flightkeys and Google[32] between January and May 2025.

Two national projects in France (DECOR) and Germany (D-KULT) have performed contrail avoidance trials with results still being analysed by the stakeholders. Two European projects (CICONIA and A4CLIMATE) have ongoing trials or have planned upcoming trials with different airlines. Finally further studies have been performed through simulation without actual rerouting (shadow mode) either at the level of an ATC region (i.e. CONCERTO project led by Thales) or an airline (American Airlines) using a flight planning tool[30].

To date, most tested contrail avoidance strategies have focused on the vertical dimension, typically by avoiding contrail-prone regions through altitude changes, most often by descending below ice-supersaturated layers. Some trials have also explored lateral rerouting[33,103], and in some occasional situations it may be pertinent to avoid contrail-prone regions by flying above them. The relative effectiveness of these different strategies, and how they should best be combined, remains largely an open question. The optimal approach is likely to depend on aircraft type and may evolve as the accuracy of weather forecasts improve. PLATT

Past contrail avoidance trials have typically been limited to samples of a few tens of flights (see Table 6) while ongoing and planned trials aim to increase this number to the order of one hundred rerouted flights. These sample sizes remain relatively small to encompass the diversity of atmospheric conditions, aircraft types, air traffic management rules, and to test the actual realisation of flight trajectories and their climate benefits in operational settings.

The decision to reroute a flight is typically based on a weather forecast combined with a contrail model, in practice most often CoCiP, and a flight planning tool that seeks to minimise an operational cost function that factors in the climate cost of contrails. A first level of verification therefore consists in assessing whether the realised flight has indeed reduced the estimated climate impact, using the same indicator as applied during flight planning. Two main factors can lead to discrepancies between the planned and realised climate impact: (i) differences between the forecast and the actual meteorological conditions, and (ii) deviations between the filed and the actual flown trajectory. Qualitative validation from existing trials generally indicates that this first level of verification is met to a significant extent, as weather forecasts relevant to contrail formation have been shown to be relatively stable[104]. Remaining discrepancies are likely to be dominated by deviations between planned and realised trajectories, the magnitude and frequency of which remain to be quantified.

A second level of verification concerns whether the simulated climate impact of a rerouted flight is consistent with its actual impact. Demonstrating such consistency is considerably more challenging. Discrepancies may arise from (i) inaccuracies in the underlying meteorological fields used in forecasts or reanalyses, independently of their temporal stability with forecast lead time, (ii) (parametric and structural) errors in models of contrail radiative impact and (iii) observational uncertainties and interpretability. This highlights the critical importance of incorporating observations of contrail radiative effects (or their absence in the case of successful contrail avoidance) into the verification framework. In practice, it is very unlikely that this second level of verification can be performed for every contrail avoidance. This means that the efficiency of different strategies will have to be assessed statistically and rely partly on models. The same holds for the verification of operational contrail avoidance policies. How the efficiency of the contrail avoidance trials depends on the source of weather forecasts will be an important consideration.

Further work is needed to refine the scope of future contrail avoidance trials[105], recognising that these trials (i) should be of longer duration (typically a year), (ii) involve substantially larger numbers of flights (typically thousands to tens of thousands), (iii) explicitly account for uncertainties in order to support risk-aware rerouting decisions[106], and (iv) rely on clearly defined modelling and observational strategies for comparing rerouted and non-rerouted flights[103]. Operationalisation of contrail avoidance strategies requires advanced flight planning tools and/or should be supported by air navigation service providers through a suitable ATM strategy. This framework could also allow for minor tactical adjustments during the flight, informed by the latest meteorological and contrail forecasts. Involvement of all stakeholders is paramount.

Contrail trials	Stakeholders, strategy and feedback from trial	Details	Fuel & Time (deviated flights)	Reference
Maastricht Upper Area Control (MUAC), 2021	Air traffic was deviated every other day by changing the flight altitude by up to 2000 ft up or down if persistent contrails were predicted. Forecasting persistent contrails was a challenge. Despite small statistics and difficulty in identifying contrails in satellite imagery, the trial was considered to be successful.	264 days, ATM-led, tactical, 3398 cases (reference), 2690 cases (deviated) but only 23 (with contrails predicted)	Not assessed	Ref. 24
American Airlines, Jan-June 2023	Trial conducted by American Airlines with contrails.org, Google and Flightkeys. Reported 64% fewer contrails in these flights relative to the control group flights.	Airline-led 22 control flights 22 deviated flights	+2% (fuel)	Ref. 31
TUIfly, September 2024	Trial conducted by TUIfly with support from DLR. Fully automated avoidance workflow, achieved 60% reduction in CO_2eq (according to model). Research shortcomings include weather related uncertainty and climate impact modelling. Preliminary results show that validation strategies need to be significantly improved. Part of the TF-100 flights trial below.	Airline-led 25 deviated flights	+2.8% (fuel) +1.7 min (time)	Ref. 33
TF-100 flights trial 2024 & 2025	TF-100 flights trial. Trial conducted by TUIfly, Lufthansa, Condor & DHL with support from DLR. Scientifically supported by the D-KULT project.	Airline-led 108 deviated flights & 61 observation flights	+1.56% (fuel) +1.13% (time)	Ref. 102 & Ref. 107
DECOR, 2025	Trial conducted by Amelia with support from Thales and Klima.	Airline-led, analysis ongoing.		
American Airlines, Jan-May 2025	Trial conducted by American Airlines with support from contrails.org, Google and Flightkeys. Reported 62% lower contrail formation rate for deviated flights relative to the flights in the control group.	112 deviated flights	No statistically significant difference in fuel usage	Ref. 32
SESAR CICONIA, 2025-2026	Trial conducted by Air France with support from Klima and Estuaire.	Airline-led, ongoing.		
HORIZON A4Climate TUIfly, 2026	Trial conducted by TUIfly.	Airline-led, upcoming. Aiming for > 400 deviations.		Ref. 103

Table 6. Summary of past and ongoing/upcoming field trials of contrail avoidance and their characteristics.

A key methodological aspect of contrail avoidance trials is the selection and sampling of rerouted flights, which may be chosen based on the potential and operational feasibility of implementing contrail-avoiding trajectories. Equally important is the construction of a suitable reference set of non-rerouted flights. This reference set can be defined in two complementary ways. In a paired design, each rerouted flight is directly compared with a non-rerouted flight that is as similar as possible in terms of season, weather situations, departure time, origin and destination, flight level, and aircraft type, allowing for a close, one-to-one assessment of the effect of rerouting. In an unpaired design, the reference set consists of a broader sample of non-rerouted flights over the same period and region, which provides a statistical baseline against which the overall effectiveness of contrail avoidance can be assessed, but without a direct one-to-one correspondence with individual rerouted flights. Both approaches are valuable: paired comparisons reduce variability due to external factors and improve the interpretability of single-flight outcomes, while unpaired comparisons enable the evaluation of broader patterns and aggregate effects across a larger set of flights.

Recommendations for future contrail avoidance trials

Recommendation #7 - A strategy for contrail avoidance trials

a) Further trials are needed to progress our understanding and implementation capability of contrail avoidance strategies. Their value would be significantly enhanced if they are conducted in a transparent and coordinated manner. The development of a set of guidelines, covering the selection of reference and rerouted flights, and a common framework for evaluation would facilitate more consistent and robust assessment of future contrail avoidance strategies.

b) The methodology and flight information associated with future contrail avoidance trials should be made publicly available to the greatest extent compatible with operational and commercial confidentiality considerations. Open data enable independent replication of individual analyses, benchmarking of verification methods across research groups, and production of meta analyses.

c) The wide range of atmospheric situations, aircraft types, potential avoidance strategies, and airspace capacity constraints justifies progressing towards large-scale trials lasting typically a year. These large-scale avoidance trials will need to be underpinned by both clear scientific objectives and operational considerations.

V. Operationalising contrail mitigation

Operationalising contrail avoidance strategies requires a significant strengthening of the observational foundation that supports detection, prediction, and verification of contrail formation conditions. From an observational science perspective, several key research and development areas need to be addressed: (i) improved characterization and forecasts of upper tropospheric humidity and temperature, (ii) continuous monitoring of contrails and contrail cirrus, (iii) digital twin of aviation impacts on contrails and induced cirrus, and their radiative impacts, (iv) validation and evaluation framework of contrail avoidance measures. We address the points below. A summary is provided in Table 7.

Current status of the observing system

Monitoring upper-tropospheric humidity and ice clouds is crucial for both research into contrail and induced cirrus and operationalising contrail avoidance strategies. Over the past decades, a range of infrared sounders, such as IASI and IASI-NG, and microwave sounders onboard satellites have provided very valuable information on the vertical profiles of temperature, water vapour, and cloud properties. Radiosondes provide high-accuracy vertical profiles of temperature and humidity at specific locations and standard launch times. Both these satellite and in situ observations are assimilated into numerical weather prediction (NWP) models. The quality of NWP forecasts and reanalysis products[108] depend also on the quality of the model and the sophistication of its cloud scheme. In particular some NWP models (such as the Integrated Forecasting System (IFS)[109] at the European Centre for Medium-Range Weather Forecasts (ECMWF), ICON at the Deutsche Wetterdienst (DWD)[110], and a new configuration of Arpege[111] at Météo-France) allow for ice supersaturation while others (such as the Global Forecast System (GFS) of the National Oceanic and Atmospheric Administration in the United States) have not yet such a capability. Data-driven approaches are also being developed.

In-service Aircraft for a Global Observing System (IAGOS) is a European research infrastructure that equips commercial aircraft with instruments to measure atmospheric composition, greenhouse gases, aerosols, and meteorological parameters during routine flights[89]. It is an integral and invaluable part of the observing system for upper-tropospheric humidity as it provides high-quality, in situ direct measurements of relative humidity with respect to ice (RHi) offering accuracy typically better than 5–10% in the upper troposphere-lower stratosphere (UT-LS) region[112]. It also has an extensive geographical coverage in flight corridors because the measurements are made from commercial aircraft operating worldwide. The program also benefits from long-term consistency as it has been operating since the mid-1990s (continuing the MOZAIC project). However the data are temporally and spatially sparse as observations depend on the routes of only a few (typically ten) aircraft from a handful (typically less than ten) airlines. The data also suffer from a long latency (i.e., delivery time) because the IAGOS humidity sensors require a post-flight calibration and the data undergo meticulous post-processing. Thus such data are essentially used for process studies and for validation of satellite and model humidity fields.

Multiple studies[113,114] have assessed the quality of the ERA5 reanalysis against IAGOS measurements. This represents a useful comparison because NWP forecasts are expected to perform somewhat less well than their corresponding (re)analysis against a benchmark such as IAGOS. While ERA5 reproduces temperature well, it is less good at representing humidity. In particular it tends to predict too low humidities (with a systematic dry bias in RHi of up to −5% at 250 hPa), leading to an underestimation of ISSR occurrence. Comparisons over tropical and extratropical regions for 2011-2022 show that ERA5 detects ISSRs less frequently than IAGOS, with equitable threat scores (ETS) between 0.2 and 0.4, and even lower values (<0.1) under cloudy conditions due to the model's saturation adjustment scheme. The reason why NWP models do not simulate humidity better is largely due to current limitations in the observing system.

This dry bias found in ERA5 translates into lower frequencies of contrail formation conditions in ERA5 compared to IAGOS. Various corrections have been proposed to correct ERA5 (and by extension IFS forecasts) using simple[115] or multivariate[113] bias correction methods. It is likely that more sophisticated machine learning methods can help further to post-process humidity fields from weather forecasts and ERA5; however the usefulness of such methods will be limited by the quantity and coverage of training data.

In conclusion, there is room for improvement in terms of ISSR forecasts and more generally weather forecasts. Improved forecasts will result in more effective contrail management strategies. However the quality of the forecasts is not seen as a show stopper for further trials and early deployment.

Future evolution of the observing system

Several new and upcoming satellites are expected to increase observing capabilities and feed into better monitoring and forecasts of upper-atmosphere humidity and cirrus clouds. The 3MI instrument onboard EPS-SG-A provides multi-angle, multi-spectral measurements of aerosols and cloud properties. The Arctic Weather Satellite (AWS) from the European Space Agency carries a cross-track scanning microwave radiometer that is now being combined into weather forecasts[116]. AWS was built as a demonstrator for a future constellation of microwave sounders called EPS-Sterna[117] that will be operated by EUMETSAT. Such a constellation would provide measurements of atmospheric humidity and temperature at a higher frequency and with less latency. A constellation of polar-orbiting satellites would effectively complement the MTG-S1 infrared sounder in geostationary orbit. While MTG-S1 provides high temporal resolution observations that capture the diurnal evolution of cloud and humidity fields, its coverage is restricted to the geostationary disk centered at 0° longitude and its viewing geometry leads to reduced spatial resolution at high latitudes. This represents a limitation for contrail avoidance that may be particularly effective in the mid-to high latitudes and over oceans. The Ice Cloud Imager (ICI) onboard EPS-SG-B (yet to be launched) will offer targeted observations of ice cloud microphysical properties. In the medium term, hyperspectral microwave atmospheric sounders represent another opportunity to improve monitoring and forecasting of humidity.

Despite these advances, the information content on ice supersaturated regions (ISSR) in satellite data is expected to remain limited due to the low specific humidity and the inherently broad vertical averaging kernels of satellite sounders, which smooth out the fine-scale vertical structure. As a result, only incremental improvements in ISSR monitoring can be expected from actual and planned satellite missions alone. **Humidity sensors that operate in situ therefore represent a promising -and arguably indispensable- pathway to enhance the atmospheric observing system to a level suitable for operational contrail avoidance.**

High-altitude balloon platforms, such as those from WindBorne[118] or Sorcerer[119], offer an interesting means for in-situ atmospheric profiling, including high-resolution vertical measurements of humidity, temperature, pressure and winds in the upper atmosphere. Unlike traditional radiosondes, which provide a single vertical profile per launch and are limited to terrestrial or island locations, high-altitude balloons can remain aloft for days to weeks and capture multiple ascent–descent profiles per flight, thereby delivering dense vertical humidity sampling in regions that are currently under-observed, such as over oceans and polar zones. Such data can then be assimilated into global forecast systems demonstrating forecast improvements. However, the integration of a constellation of such persistent balloon systems into airspaces shared with aircraft (typically FL300 to FL400) poses operational and safety challenges, highlighted by the fact that even lightweight unmanned airborne systems require careful coordination to avoid collisions with crewed flights, and that regulatory frameworks for their coexistence in controlled airspace are still evolving. Respecting airspace safety requires enhancements in tracking, coordination and real-time deconfliction tools so that the scientific value of extended humidity observations can be realised without compromising aviation safety.

In situ humidity sensors onboard commercial aircraft is probably the most promising approach. Current commercial sensors do not have the required accuracy to detect ISSR at low temperatures[120]. **To be viable at scale, such sensors must be relatively low-cost, permanently integrated into aircraft systems, and require minimal maintenance and recalibration, in contrast to the more complex research-grade instruments deployed within the IAGOS network.** One advantage of using commercial aircraft is that they sample exactly the regions that are of interest for contrail avoidance. However sampling upwind regions is also essential for accurately predicting ISSRs in air traffic regions. Optical (laser-based) humidity sensors[121,122] hold a lot of promise, though some challenges remain regarding long-term stability and consistency across temperature and pressure levels.

While ongoing studies are addressing this question, **further studies will be required to assess the minimum accuracy of such instruments, the equipment rate of**

commercial aircraft and/or the density of high-altitude balloon measurements. Observing System Experiments (OSEs) and Observing System Simulation Experiments (OSSEs) are a powerful framework to quantitatively assess the potential impact of new or enhanced observations on NWP. Typically OSSE consist in (i) creating a "truth" atmosphere from a high-resolution numerical model simulation that serves as the reference against which forecast improvements are evaluated, (ii) simulating synthetic satellite and in situ observations that include noise and biases to mimic expected sensor performance, (iii) assimilating such synthetic observations into an NWP system alongside the existing operational observing network, and (iv) comparing analyses and short-term forecasts against the reference run to quantify the added value of the new data and determine the minimum accuracy required, the optimal spatial and temporal coverage, and the saturation point beyond which adding more observations no longer provides substantial benefit. OSEs have the advantage over OSSE that they do not rely on synthetic data, but instead remove or withhold real observations from the operational assimilation system to quantify their actual impact on analyses and forecasts. As such, OSEs provide a more direct and observation-based estimate of added value, albeit constrained by the existing observing system and by the impossibility of testing instruments that are not yet deployed.

	Observing component	**Remark**
In situ	Radiosondes	Assimilated in NWP models. Limited coverage.
	Profiling high-altitude balloons	Experimental but with potential.
	Research-grade humidity sensors onboard commercial aircraft (IAGOS)	Useful for model evaluation. Technology cannot be scaled up.
	Low-maintenance, stable humidity sensor onboard commercial aircraft	Under study. Desirable.
Satellite	Hyperspectral infrared sounders (e.g. IASI)	Assimilated in NWP models.
	Microwave sounders (e.g. Arctic Weather Satellite)	Assimilated in some NWP models.
	Constellation of microwave sounders.	Forthcoming (e.g. STERNA)
	Hyperspectral microwave sounders	Under study. Desirable.

Table 7. Existing, forthcoming and desirable components of an observing system for contrail mitigation strategies.

It is also likely that such in situ measurements would contribute to enhancing the value of satellite data by providing "anchors" for the IR and microwave sounders. **It is recommended to explore closer synergies between the aviation industry and the meteorological community to enhance the quality and usefulness of weather forecasts in the UTLS region. If contrail avoidance is operationalised over a region, the number of measurements from commercial aircraft in ISSRs would drop, thus**

putting limitations on how such regions would be sampled. This is another reason why a combination of in situ and satellite observations is needed.

Current and future NWP capabilities

Numerical weather prediction (NWP) models have shown some skill to predict ISSR against IAGOS and radiosonde data, though the skill varies with model and with model configurations. One study[104] showed good stability of the IFS HRES NWP system when forecasting ISSR at different lead times. However there is more consistency between the forecast and the reanalysis (ERA5) than between ERA5 and the IAGOS reference data, showing room for improvement. An NWP system capable of forecasting ice-supersaturated regions (ISSRs) for contrail avoidance typically require to explicitly represent supersaturation with respect to ice, for instance through a two-moment microphysical scheme that simulates both ice crystal number and mass concentrations, allowing realistic treatment of cirrus formation and decay under supersaturated conditions. It would need to be constrained by high-accuracy humidity observations in the upper troposphere and lower stratosphere, assimilated using methods that can handle the distribution tail of relative humidity over ice (RHi) typical of this region. **The objective should be to forecast ISSRs with lead times of 12–48 hours, suitable for pre-tactical contrail avoidance planning.**

For tactical contrail avoidance, shorter-term data-driven nowcasting capabilities could complement NWP, most likely by exploiting AI and machine learning methods trained on past observations of humidity but also of patterns of contrails and cirrus development. Observations of contrail outbreaks and induced cirrus could be traced back in time and used as an indicator of ISSRs to be avoided.

Crucially, the NWP system must also quantify and communicate uncertainty in RHi and ISSR forecasts. While ensemble prediction systems already provide probabilistic information, structural model biases mean that the true uncertainty is likely underestimated.

A next-generation NWP framework for contrail avoidance would thus combine physically consistent microphysics, dense humidity observations, and advanced data assimilation. It should be underpinned by rigorous uncertainty characterization, e.g. in the form of ensemble forecasting. Until forecast accuracy reaches a satisfactory level, the framework should build on a multi-model approach and integrate an hybrid AI-driven nowcasting capability rather than rely on a single source of forecast.

Verification: a mix of observations

Verification of contrail avoidance strategies requires a dedicated observational and data-integration infrastructure, even if, as discussed above, verification does not need to be performed for every single avoidance manoeuvre. A statistically robust sampling framework may be sufficient, provided it captures the relevant regions, meteorological regimes, aircraft types, and traffic densities. **Thus verification should be envisaged to be statistical in nature rather than attempt to target each contrail.**

Such a framework should rely on a combination of spaceborne and ground-based observations. **Satellite observations** (polar and geostationary) enable the detection and tracking of contrails and contrail cirrus. **Ground-based observations** are essential for validating satellite retrievals and characterizing young contrails that may be difficult to detect from space. Integrating heterogeneous imaging capabilities across platforms, with differing spatial resolution, viewing geometry, spectral characteristics, and revisit time, will be critical. This implies rigorous co-location and time-matching procedures and consistent contrail detection and classification algorithms. Verification should be combined with realised aircraft trajectories and high-resolution meteorological analyses. These data streams form the basis for a contrail avoidance digital twin.

Recommendations to progress operationalisation

Recommendation #8 - Humidity sensors onboard commercial aircraft
Enhancing operational contrail avoidance requires improving observations of ISSRs beyond what current and planned satellite missions can provide. Humidity sensors aboard commercial aircraft offer a promising and potentially indispensable pathway, provided they have a sufficiently low detectability limit, are stable, and require minimal maintenance and recalibration. Further Observing System Experiments (OSEs) and Observing System Simulation Experiments (OSSEs) are needed to establish the relevant requirements.

Recommendation #9 - Improving further NWP forecasts
Current NWP models are accurate enough for contrail avoidance trials but should be intercompared and improved to support operational contrail avoidance. Enhancing existing models with improved physical representations and further data assimilation of humidity observations could substantially increase forecast skill. Hybrid AI-driven nowcasting could complement traditional NWP forecasts, providing a seamless strategy for both pre-tactical and tactical contrail avoidance.

Recommendation #10 - A contrail avoidance digital twin
Operational contrail avoidance requires a digital twin to simulate the climate impact of contrails and contrail mitigation measures. Such a tool may rely on a physics-based approach (i.e. grounded in physical principles), a data-driven approach (i.e. trained on historical observations), or adopt a hybrid approach combining elements of both, but the overarching priority is that they remain unbiased with respect to a benchmark dataset. Higher model accuracy will translate into enhanced operational efficiency, as better predictions allow for more targeted and cost-effective avoidance strategies. Such a tool will benefit from a clear definition of both requirements and measures of success against an agreed benchmark.

VI. R&D roadmap

Building on the set of recommendations, we propose a roadmap structured around six objectives: three objectives address the fundamental science of contrails (Figure 12) while the other three focus on enabling technologies in relation to atmospheric sciences (Figure 13).

The fundamental science objectives are organised along the characteristic timescales of contrail evolution, namely formation (the jet regime), growth and decay (the vortex and diffusion regimes), and the subsequent atmospheric adjustments. In parallel, the enabling technology objectives target key observational and modelling capabilities required for operationalisation, including atmospheric humidity measurements, improved weather forecasting systems, and the development of a digital twin framework for contrail avoidance.

While these six objectives should largely be pursued in parallel in order to reinforce and accelerate the overall effort, progress within each can be staged and coordinated. The progression is expected to be punctuated by (i) model intercomparison studies[99], (ii) new dedicated in-flight field campaigns that would follow up the ECLIF3 and the VOLCAN campaigns, (iii) the launch of new spaceborne Earth Observation satellites with MTG-S1 (first infrared sounder on a geostationary orbit), MTG-I2 (a new imager on a geostationary orbit with a very rapid scan) and the Sterna microwave sounders, (iv) small-scale contrail avoidance trials, followed ultimately by (v) a large-scale demonstrator in the early 2030s.

A key component will be to integrate the different observational data streams, including from LEO (Low Earth Orbit) and GEO (Geostationary Equatorial Orbit) satellites, into estimates of the radiative impact of contrails and induced cirrus so that the benefits of contrail avoidance can be assessed at the regional and seasonal levels. Such data should integrate a digital twin for contrail for contrail avoidance.

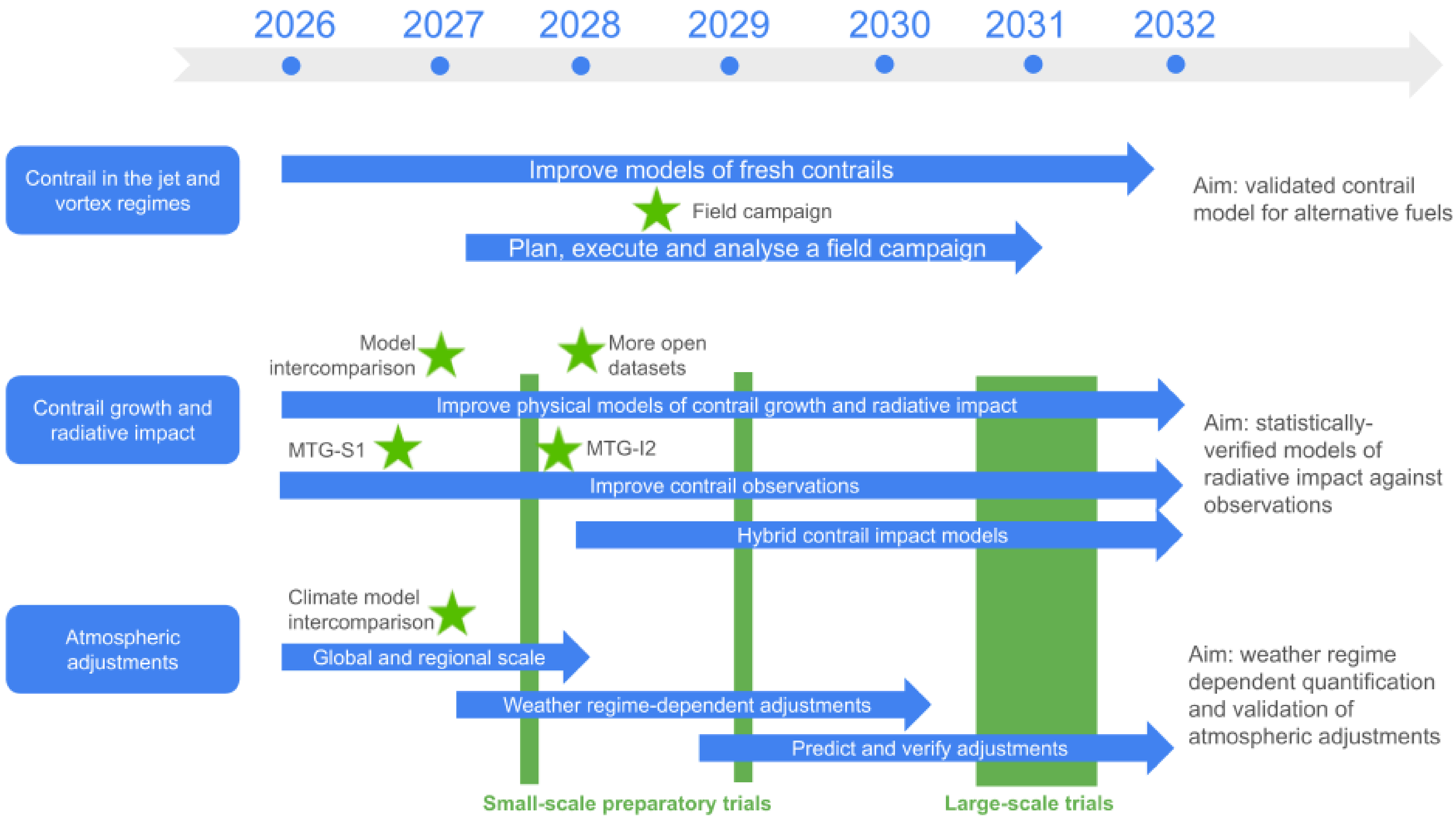


Figure 12. Proposed roadmap to strengthen the fundamentals in contrail science for operational contrail avoidance.

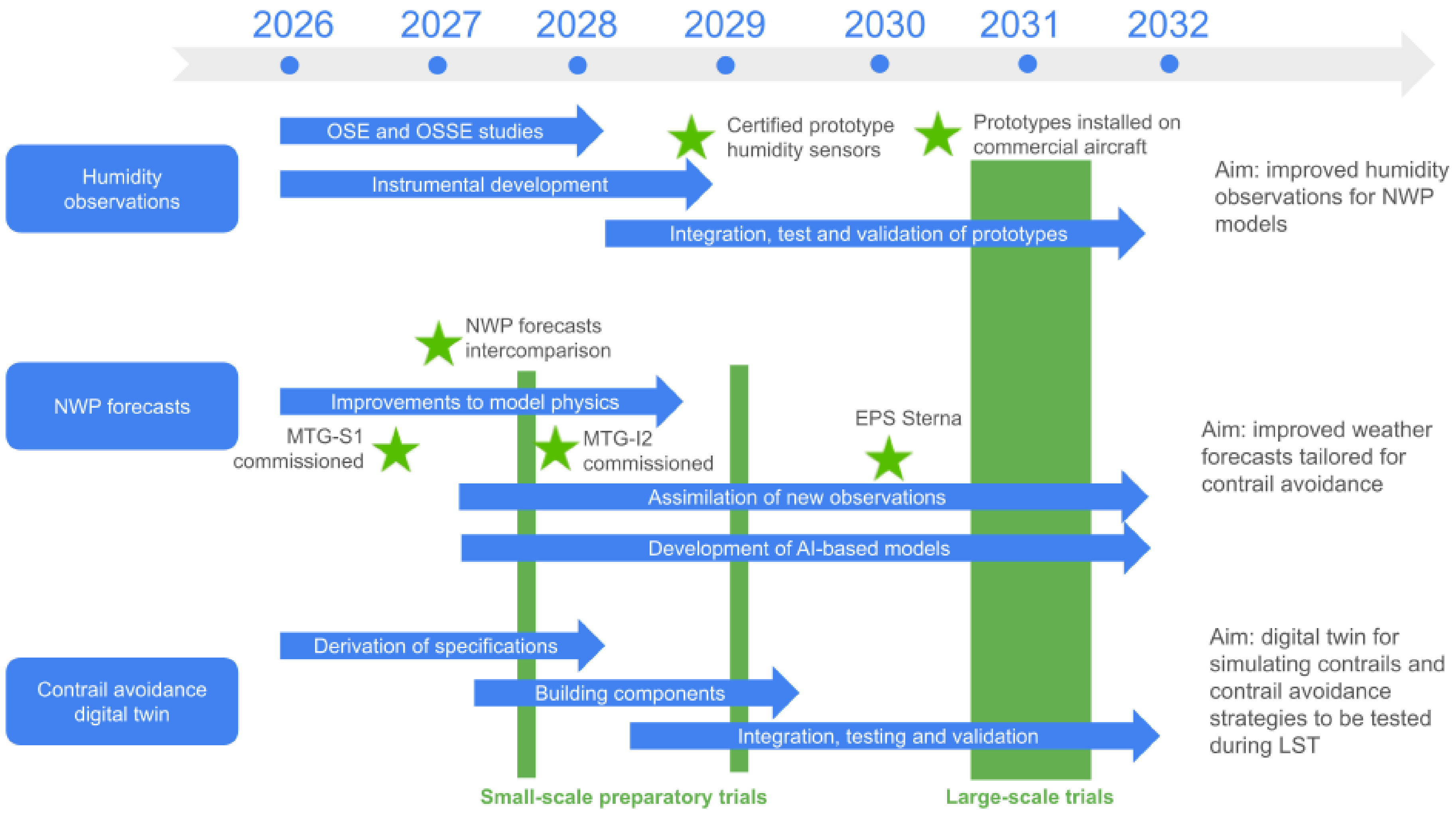


Figure 13. Proposed roadmap to advance the enabling technologies in atmospheric sciences required for operational contrail avoidance.

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Annex I: SWOT analysis of contrail mitigation strategies

Contrail avoidance through flight scheduling

Strengths	Weaknesses
No-regret solution if a fraction of aircraft operations is shifted from times when contrails have definite warming effects to times when contrails have neutral or cooling effects. Can be planned long ahead based on climatologies of contrail climate impact. Little to no impact on Air Traffic Management as part of current procedures.	Potential is uncertain but likely small. May cause significant constraints on traffic capacity, airport capacity and airlines hub operations. Economic implications for airlines if it results in a lower aircraft utilization rate.
Opportunities	**Threats**
Can also be applied to some military routine operations.	

Contrail avoidance through pre-tactical flight rerouting (airline-led)

Strengths	Weaknesses
May not require active cooperation from ATC in the case of lateral rerouting. Trials are simpler to set up and may not initially require active cooperation from ATC. Integrate well with fuel optimisation strategies.	May generate capacity problems if not coordinated. More difficult to verify using satellite data as attribution of individual contrails to particular aircraft can be ambiguous in the presence of other aircraft, especially if implemented initially in low density air traffic regions. Effectiveness may be reduced if the climate impact of contrails saturate (i.e. a reduction in contrail-forming flights does not result in a corresponding reduction in contrail climate impact).
Opportunities	**Threats**
Appropriate for regions with low density traffic. May be performed by voluntary airlines, at least initially. No-regret strategy if only nighttime contrail and contrail cirrus are targeted.	Risk of additional fuel burn if ATC does not facilitate trajectories involving vertical rerouting. Uncertainties on the additivity of the climate effects of contrails at a given location and time limit the potential benefit in high density air traffic regions. Requires an incentivisation scheme for upscaling.

Contrail avoidance through pre-tactical flight rerouting (ATM-led)

Strengths	Weaknesses
More effective for high density traffic regions. Easier to verify using satellite data as attribution of individual contrails to particular aircraft is less critical.	Requires active involvement of and coordination between ATC authorities. Potentially less fuel efficient if performed tactically as it would imply a systematic extra fuel load. Does not integrate well with fuel optimised strategies. More difficult to verify using satellite data as attribution of individual contrails to particular aircraft can be ambiguous in the presence of other aircraft.
Opportunities	**Threats**
Easier to design strategies for contrail avoidance trials (in particular by altering avoidance and non-avoidance days).	Lack of consistency in contrail avoidance strategy across ATC areas.

Contrail avoidance through tactical flight rerouting

Strengths	Weaknesses
Based on near-real-time observations of humidity and contrail-prone atmospheric regions. Could rely on relatively small adjustments to flight routes.	Potential may be more limited than for strategic flight rerouting that occurs at the pre-flight phase. Effectiveness may be reduced if a few flights cross the contrail-probe region before other flights avoid it. May require loading additional fuel even for flights that are eventually not rerouted tactically.
Opportunities	**Threats**
Promote real-time collaborative information sharing across the aviation ecosystem.	Increased airspace congestion. Complexification of air traffic management.

Contrail management through targeted use of alternative fuels

Strengths	Weaknesses
Much simpler to implement from an ATM viewpoint. Does not generate additional capacity problems. Complementarity with ATM-led contrail avoidance by allowing aircraft powered with alternative fuel (SAF, hydrogenated kerosene) in otherwise restricted air spaces.	May depend on many other parameters such as ambient aerosol concentrations, engine characteristics and maintenance, lubricating oil. More complicated implementation in terms of ground operations as it may require distribution of several fuel types. Not well aligned with ATM-led contrail avoidance strategies in the case of blanket restrictions applied uniformly across contrail-prone regions. Modifying the blending rate of SAF at airports may require new infrastructure.
Opportunities	**Threats**
Appropriate for both low-density and high-density traffic regions. Impact could be leveraged by increasing the SAF blending rate for targeted flights as high warming potential May be performed on a voluntary basis, at least initially.	Science is more uncertain than for airline-led or ATM-led contrail avoidance, and potential may be more limited than anticipated. SAF availability and traceability is limited.