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Design Principles for a Contrail-Minimizing Trial in the North Atlantic

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Abstract: The aviation industry has committed to decarbonize its CO_2 emissions. However, there has been much less industry focus on its non-CO_2 emissions, despite recent studies showing that these account for up to two-thirds of aviation's climate impact. Parts of the industry have begun to explore the feasibility of potential non-CO_2 mitigation options, building on the scientific research undertaken in recent years, by establishing demonstrations and operational trials to test parameters of interest. This paper sets out the design principles for a large trial in the North Atlantic. Considerations include the type of stakeholders, location, when to intervene, what flights to target, validation, and other challenges. Four options for safely facilitating a trial are outlined based on existing air-traffic-management processes, with three of these readily deployable. Several issues remain to be refined and resolved as part of any future trial, including those regarding meteorological and contrail forecasting, the decision-making process for stakeholders, and safely integrating these flights into conventional airspace. While this paper is not a formal concept of operations, it provides a stepping stone for policymakers, industry leaders, and other stakeholders with an interest in reducing aviation's total climate impact, to understand how a large-scale warming-contrail-minimizing trial could work.

Keywords: aviation; climate change; non-CO_2 emissions; contrails; mitigation; North Atlantic; air traffic management

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1. Introduction

The understanding of aviation's climate impacts has improved significantly in recent years, in particular with respect to non-CO_2 effects, such as nitrogen oxide, particulate matter, and contrail cirrus [1]. This has, in part, led to increased concerns about the lack of action or targets to reduce the industry's total climate impact. Since the signing of the United Nations Framework Convention on Climate Change and the adoption of the Kyoto Protocol in 1997, action by the aviation industry has focused almost exclusively on reducing CO_2 emissions. This is due to the relative ease with which CO_2 can be measured and modelled, and a perceived lack of scientific certainty on non-CO_2 effects. However, as the most visible climate impact of aviation, contrails are a special form of cirrus cloud which contribute to radiative forcing. The Intergovernmental Panel on Climate Change special report on aviation's climate impact [2], commissioned in 1997 by the International Civil Aviation Organization (ICAO), was clear that aviation's non-CO_2 impacts are potentially larger than those of CO_2 alone. Recent research indicates one-third of the global effective radiative forcing (ERF) from aviation activity arises from CO_2 emissions and two-thirds from non-CO_2 emissions, and the global annual mean ERF from contrail cirrus could be comparable to or larger than the ERF that arises from aviation's cumulative CO_2 emissions since the start of commercial air travel [1].

Given the evolution in the scientific understanding of aviation's non-CO_2 emission impacts, questions now exist with regards to: (i) which metrics are appropriate for measuring aviation's overall climate impacts; (ii) what timescales should be used to measure those impacts considering the shorter lifespan of contrail-induced cirrus relative to CO_2 emissions; and (iii) how we should assess interdependencies to consider mitigating aviation's non-CO_2 climate impacts? Arguably, the answer to these questions was decided when governments agreed to hold temperature increases from climate change to 1.5–2 °C by 2050. As a result, the implications for aviation are clear—the industry must act to reduce its total climate impact from both its CO_2 and non-CO_2 components, and it must do so quickly if this policy objective is to be achieved by 2050. Hoping for unprecedented levels of sustainable alternative fuel, a complete fleet renewal with new propulsion systems (e.g., electric or hydrogen), airspace modernization, market-based measures, or other solutions to begin to reduce the sector's climate impact in the coming decades, as suggested by industry roadmaps [3] and others [4,5], will be challenging given their limited success in meeting environment targets to date [6]—and this raises the question of what action can be taken in this decade. Relying on future technology fixes also negates the cumulative climate impact caused by aviation's increasing CO_2 and non-CO_2 emissions between now and 2050. This is in comparison to other sectors, who are already decarbonizing, leading aviation's contribution to anthropogenic climate change to grow as a proportion of the total [7].

Compared to the above options, there are two relatively 'quick fixes' which can be considered in the near term. The first is to ensure aircraft operators are not financially incentivized to flight-plan longer routes than necessary, which incur additional CO_2 emissions, to avail themselves of cheaper air traffic control (ATC) charges [8]. Rectifying this may have specific cost and policy implications for aircraft operators and air navigation service providers (ANSPs) but are not insurmountable [9]. The second near-term option, which is the focus of this paper, is to minimize persistent, highly warming contrails from aircraft. The pros and cons for industry-wide persistent warming-contrail-minimizing strategies are becoming more widely understood and of interest [10–14], including through a new initiative by ICAO's Committee on Aviation Environmental Protection on contrail avoidance. This follows the first formal trial led by an ANSP in 2021 [15], an aircraft operator-led trial which began in 2022 [16], while a limited number of other demonstration flights have also been undertaken [17] and others are proposed or planned.

This paper draws on the latest scientific understanding of the formation, lifecycle, and climate forcing of contrails and contrail-induced cirrus, and combines it with detailed knowledge of ATC operations in order to set out the design principles for how a contrail-minimizing trial in the North Atlantic might be conducted safely.

2. State-of-the-Art: Contrail Impacts and Mitigation

Contrails form under specific atmospheric conditions with high humidity and low temperatures, and are made up of ice crystals that predominantly arise from non-volatile particulate matter (nvPM) particles emitted by aircraft engines [18]. Most contrails that form in warmer and drier air generally sublimate a few minutes after formation [19]. However, around 10–20% of contrails are formed in regions where the relative humidity with respect to ice exceeds 100% [20,21], and these contrails can persist, spread, mix with other contrails and natural cirrus, and evolve into contrail cirrus with observed lifetimes of up to 19 h [22–24]. These ice-supersaturated regions (ISSR) are more common in the upper troposphere at altitudes of 8–13 km and exhibit seasonal patterns with larger horizontal and vertical coverage during the winter [21,25].

Globally, the annual mean contrail cirrus coverage as a percentage of sky area is estimated to range between 0.1 and 0.4%, and up to 10% in airspace with a high air-traffic density such as the North American east coast and Europe [26–28]. The presence of contrail cirrus changes the radiative balance at the top of the atmosphere: contrails trap outgoing longwave radiation at all times and cause a greenhouse effect; but during daylight hours, they can also contribute to a cooling effect by reflecting incoming solar radiation back to space [29]. The magnitude of contrail climate forcing is determined by how much the cooling and warming effect cancel each other out, and on aggregate, the scientific consensus is that the net effect of contrails globally is a warming contribution [1].

Several metrics have been used to quantify contrail climate forcing and compare it with other pollutants, such as: (i) radiative forcing (RF, in W m^{-2}), which estimates the instantaneous change in radiative flux at the top of the atmosphere over a spatial domain at a given point in time; (ii) effective radiative forcing (ERF, in W m^{-2}), which accounts for the second-order atmospheric response that is caused by the contrail, including changes in the lapse rate; ambient humidity; and natural cirrus occurrence and properties; and (iii) energy forcing ($EF_{contrail}$, in J), which quantifies the cumulative radiative effect from the contrail over its lifetime [12,30]. The RF and ERF are normally defined as global mean values and are usually adjusted to stratospheric equilibrium, while the $EF_{contrail}$ uses the local and instantaneous RF values (change in radiative flux per contrail area) and estimates the total climate forcing from individual contrail segment or flights. The global annual mean contrail cirrus net RF (111 [33, 189] mW m^{-2}, 95% confidence interval) and ERF (57 [17, 98] mW m^{-2}) in 2018 could exceed that of the forcing from aviation's cumulative CO_2 emissions since its inception (RF and ERF of ~34 [28, 40] mW m^{-2}) [1], and a recent study found significant interannual variability in the annual mean contrail cirrus net RF over the North Atlantic (204–280 mW m^{-2}) [21].

To reduce the contrail climate forcing, mitigation solutions could be targeted at those flights which produce persistent warming contrails including: (i) the use of sustainable alternative fuel, which reduces nvPM particles, contrail optical depth, and RF [31–33] (but supply remains severely constrained at the present day [34,35]); or (ii) flight-diversion strategies that minimize the formation of strongly warming contrails [30,36]. We note that solution (ii) does not require the avoidance of all contrails because ~70% of contrails formed over the North Atlantic are short-lived with negligible radiative significance, and ~20% of persistent contrails have a net cooling effect [21]. It is also critical that flight-diversion strategies should also account for the quality of meteorological forecasts and the operational constraints of air traffic management (ATM) and aircraft operators, e.g., airspace complexity, flight planning, cost efficiency, safety, and workload.

In 2021 Maastricht Upper Area Control Center (MUAC) and the German Aerospace Center undertook a contrail prevention trial, targeting flights in their cruise phase at nighttime which were more likely to create persistent warming contrails [37]. The strategy was for ATC to be provided with information on ISSRs and to tactically request that the flight crew climb or descend by 1000 ft or 2000 ft to avoid contrail formation by routing above or below these regions. No horizontal changes to trajectory were planned. The trial lasted 120 days, with interventions only on alternate days (subject to meteorological conditions) to allow the creation of a control sample. In 2022 Etihad Airways, in conjunction with SATAVIA, began a program of weekly contrail avoidance flights across their route network [16]. The intervention was mainly pre-tactical, i.e., in advance of a flight, on a selected route which had a high likelihood of passing through ISSRs. The flight plan was adjusted so that it minimized contrail formation, subject to airspace network constraints. The trial typically targeted one flight per week, subject to meteorological conditions, over an expected 12 months.

3. Considerations for a Contrail-Minimizing Trial

Minimizing persistent-warming-contrail formation and its associated climate forcing can be achieved in several ways, including altering the engine design, the properties of the fuel, or the trajectory of a flight to avoid ISSRs where contrails are likely to form and persist. Minimizing warming-contrail formation by avoiding flying aircraft through

ISSRs could be considered the preferred strategy to mitigate aviation's climate impact in the short/medium term, especially if only targeting persistent contrails. Various studies have already considered the potential for a minimal contrail strategy involving aircraft operators and/or ANSPs [21,30,36,38–44]. This section builds on these to set out the initial considerations for a trial to minimize persistent-warming-contrail climate forcing, including the ATM strategies to manage it safely.

Given the very recent developments and increasing interest in reducing the non-CO_2 climate impacts of aviation, the primary aim for any trial of this nature is to test the operational feasibility of minimizing persistent or strongly warming contrails, including assessing the operational decision-making processes, flight planning, ATM, workload, and validation of the forecasts and outcome. Ideally the approach to take would be to incorporate contrail minimization as part of the aircraft operator's flight plan, supported by the ANSP with an appropriate ATM strategy, potentially allowing for minor tactical adjustments mid-flight based on the most recent meteorological and contrail forecasts.

A number of factors are relevant to setting out the principles of a contrail-minimizing trial, which are briefly highlighted below.

3.1. Stakeholders

The first factor is the stakeholders involved in a trial, including their role and ambitions. The aviation industry is deeply interconnected and aviation stakeholders often both enable and depend on each other. The key stakeholders in a trial should include an aircraft operator, a meteorological and/or contrail forecast provider, a flight plan provider, an original equipment manufacturer, and an ANSP. Each have different but complementary roles and responsibilities. Trials and demonstrations conducted to date have been individually initiated by the above stakeholders; however, no stakeholder can effectively deliver a contrail-minimizing strategy on their own and a collaborative approach is necessary to achieve a successful outcome.

3.2. Location

The geographic scope of the trials undertaken to date has varied, from relatively small in the case of Maastricht airspace (0.26 million km^2), to flights over 5000 km in length for the Etihad Airways trial across multiple European Flight Information Regions (FIR) [16]. The longer the flight, the greater the opportunity to demonstrate a contrail-minimizing strategy and test the parameters of interest because there are more opportunities for intervention and interventions can be kept in place for longer periods of time. The trial location should be large enough to be able to inform the potential widespread adoption of contrail-minimizing strategies in the future. Several ANSPs and FIRs exist across Europe, so for trial purposes it might be simpler to focus on a single ANSP with a large FIR due to the reduced requirement for cross-border collaboration (see Figure 1).

Shanwick FIR is in the north-east section of the North Atlantic and is managed by NATS, in conjunction with the Irish Aviation Authority. It covers ~2.2 million km^2 and typically handles ~80% of North Atlantic oceanic traffic. The operation of Shanwick FIR (and other oceanic air traffic services including the adjoining Gander FIR to the west which is managed by NAVCANADA) differs from most domestic air traffic control as historically there has been limited surveillance of oceanic flights due to the lack of ground-based primary and secondary radar. Consequently, procedural-based separation standards and an Organized Track Structure (OTS) have been adopted to safely manage traffic. The recent deployment of satellite-based surveillance, via Automatic Dependent Surveillance-Broadcast (ADS-B), has allowed a reduction in these procedure-based separation standards, with longitudinal separation now 14 nautical miles and lateral separation now 19 nautical miles. This has enabled greater airspace capacity and flexibility for those ANSPs who manage oceanic airspace by allowing them to provide a more efficient service to aircraft operators. This flexibility has impacted how the OTS is used and the reduction in separation requirements and increase in surveillance capability also enables the strategy outlined in Section 4.

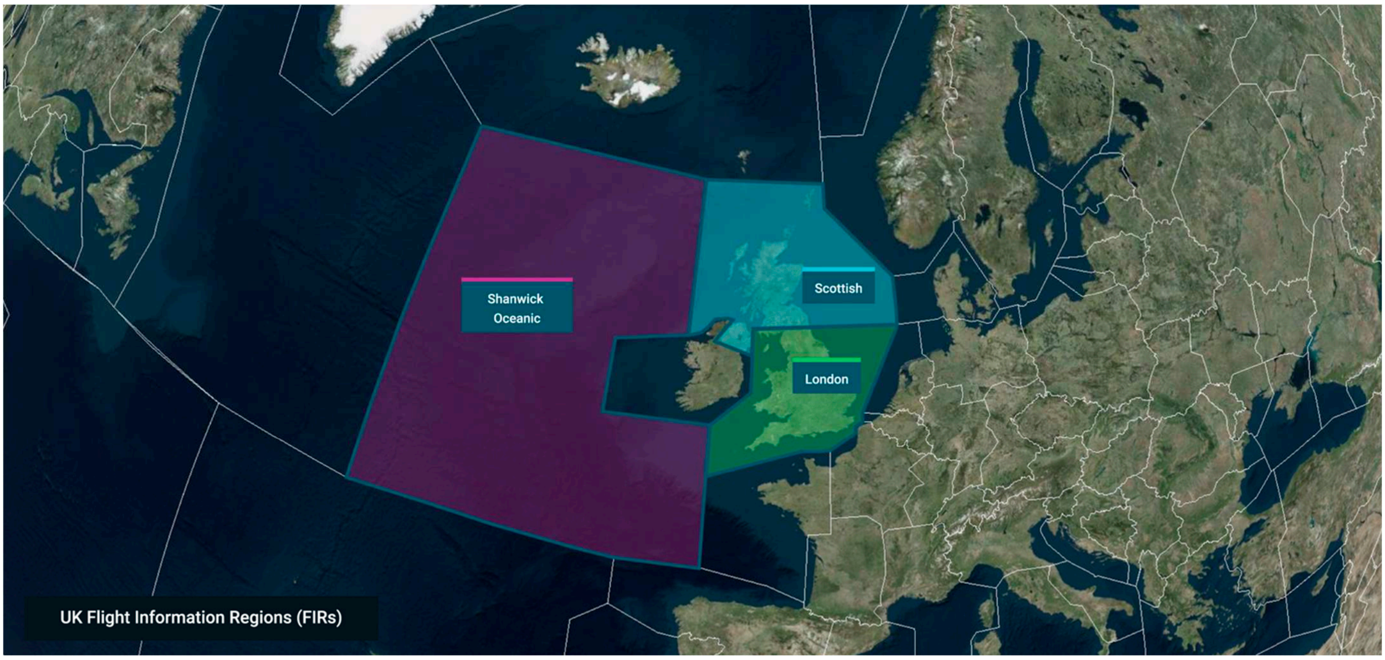

Figure 1. Map of Flight Information Regions managed by NATS [45].

An additional advantage of basing a trial in Shanwick FIR and using its associated procedural ATM approach is that traffic flows are mainly homogeneous, i.e., almost all traffic is already in the enroute phase of flight (as opposed to climbing or descending), and flights have reached the altitudes where persistent contrails are most likely to form. The traffic flows are also diurnal; with peaks departing Europe westbound in the morning and departing North America eastbound in the evening. The main directional flow can account for over 90% at peak times. An airspace like Shanwick FIR with relatively low complexity [46] and fewer boundary constraints is potentially more flexible for rerouting aircraft, subject to separation requirements. Given the long distances of flights in oceanic airspace, there is greater contrail mitigation potential in a single managed airspace, as any intervention introduced may be maintained for hours by a small number of air traffic controllers with minimal changes by the flight crew. In addition, as Shanwick FIR is systemized; if an appropriate contrail mitigation action is successful for one aircraft, and if the aircraft behind it is on the same trajectory, it is likely to also avoid contrail formation.

The North Atlantic region is not, however, representative of global or regional traffic patterns. Oceanic clearance and procedural separation are not typical in domestic airspace where conventional radar is used for surveillance. Nor are long distance homogenous traffic flows normal outside of oceanic airspace, although there are a small number of countries where it is possible to travel equivalent distances of the OTS overland. However, Shanwick FIR does provide an ideal test location for an oceanic trial.

3.3. When to Plan the Intervention

The third factor is whether the action to avoid contrails is taken: (i) pre-tactically, i.e., typically one day in advance (D-1) of when the flight is being planned to operate; (ii) tactically, i.e., during the flight as with the MUAC trial; or (iii) a hybrid of (i) and (ii). There are advantages and disadvantages to each option (see Table 1) and a critical factor will be the accuracy and stability of the contrail forecast. The contrail minimization trials undertaken to date have highlighted this challenge in particular as it affects operational decision making. Even small changes to the ISSR forecast between the days before the flight and the day of the flight may require a slightly different trajectory (see Figure 2). Although the trajectory changes are subtle, the threshold for decision making is 1000 ft vertically, i.e., the action can be as little as flying 1000 ft higher or lower than the initial filed flight plan. As part of a trial or for more widespread future deployment, an aircraft operator would potentially require meteorological/contrail forecasts to predict where and when an ISSR is likely to form with 1000 ft vertical accuracy at least 24 h in advance. The validation requirements and options are also relevant and are discussed further below. Given the current challenges in predicting persistent contrails [47–51] careful consideration should be given to the intervention types outlined in Table 1, although real-time in situ measurements may mitigate the problem, as well as allow further comparisons and correction factors to be analyzed [21].

Table 1. Pros/cons for intervention types.

Intervention	Advantages	Disadvantages
Pre-tactical	• Can be initiated by the aircraft operator or ANSP. • Action is incorporated into the flight plan which is submitted to the ANSP in advance (ideally D-1), which allows for advanced coordination and incorporation of aircraft flight plan into the daily ANSP plan. • Minimizes workload of flight crew and air traffic controllers and allows for facilitatory measures to be introduced by either aircraft operator or ANSP, e.g., altered staffing rosters, airspace sector configuration. • Time is available for the project and aircraft operator/ANSP support teams to plan and optimize the trajectory.	• Contrail forecasts may change between submission of flight plan (D-1) and the flight, meaning that the flight-plan rerouting may not be effective for contrail mitigation. • Changing the trajectory after the flight plan has been filed may require additional coordination with multiple ANSPs. • The onus is on the aircraft operator, flight-plan provider, meteorological/contrail forecast provider, or ANSP to devise the measures without all the relevant information, e.g., aircraft weight, departure time, airspace restrictions, and weather.
Tactical	• Can be initiated by the aircraft operator or ANSP. • Most recent or real-time contrail forecast can be used for trajectory optimization through more accurate predictions. • All flight parameters are known, e.g., aircraft weight, departure time, airspace restrictions, and weather, allowing for refinement of the optimal trajectory. • Allows for flexibility where dynamic ATC factors are known (e.g., airspace demand, aircraft performance) to enable contrail minimization.	• Increases workload for flight crew and air traffic controllers (and support teams) and does not allow for facilitatory measures to be introduced by either aircraft operator or ANSP, i.e., altered staffing rosters/sector groupings. • The request may not always be facilitated as it depends on traffic levels, sector capacity, airspace restrictions, etc. • Less time is available for the project and aircraft operator/ANSP support teams to plan and optimize the trajectory from when all the relevant information becomes available.
Hybrid	• Allows for advance coordination and incorporation into daily ANSP plan, albeit with some uncertainty of the final trajectory • All relevant information will be known by the time of flight, i.e., aircraft weight, departure time, airspace restrictions, and weather.	• Some additional workload required by flight crew and air traffic controllers. • Some uncertainty on whether the updated trajectory will be achieved.

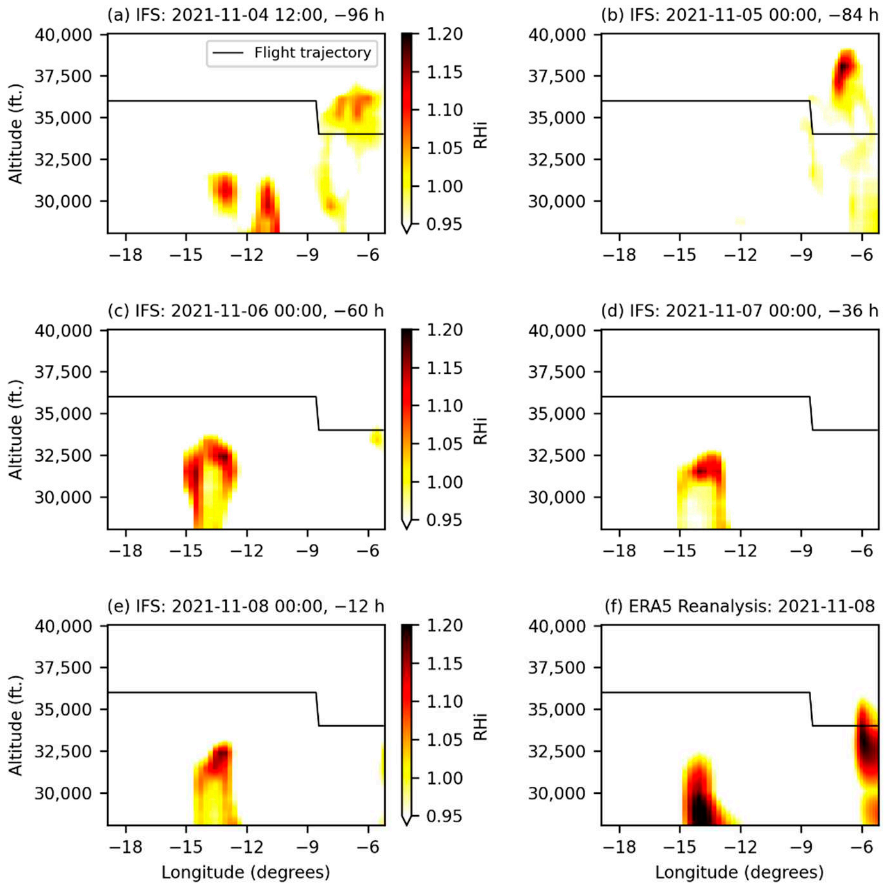

Figure 2. Evolution of ISSR forecasts provided by the European Centre for Medium-range Weather Forecast (ECMWF) Integrated Forecast System between T-96 h (panel a) and T-12 h (panel e), and the actual ISSR encountered during a flight (panel f) provided by the European Centre for Medium-range Weather Forecast (ECMWF) ERA5 High-Resolution Realization Reanalysis.

Notwithstanding the current limitations of meteorological/ISSR forecasting (see Figure 2), it is desirable to act pre-tactically to allow the ANSP to incorporate the minimal warming-contrail strategy request into the overall tactical delivery plan of the ATC service on the day of operation. Acting tactically to minimize warming contrails will likely increase the workload for both the flight crew and air traffic controllers and is less certain to be facilitated given the request is for a different trajectory to what has been filed by the aircraft operator. A hybrid approach would incorporate changes to the flight plan at D-1, supplemented by additional minor tactical requests on the day of operation to further minimize contrails. Each of these options may entail a different ATM strategy, discussed in the next section.

3.4. What and Where to Target

The fourth factor is the targeting of candidate flights for minimizing contrails, including time, season, location, number of flights, etc. (see Figures 1 and 4 of Teoh et al. [21]). Any trial will only ever involve a sample of flights, with the consent of the relevant aircraft operator, who is responsible for the planning and operation of the flight. ANSPs manage the airspace network, while aircraft operators are responsible for route planning and are subject to following ATC procedures and network restrictions. ANSPs cannot arbitrarily direct aircraft operators to flight-plan in a particular way or along a particular route. As a result, a prerequisite for a trial in the North Atlantic will be an active aircraft operator stakeholder.

The time of day is relevant given the diurnal flow of traffic in the North Atlantic and for targeting the aircraft operator's winter/summer schedule. If the trial targets winter westbound nighttime flights, which have prepared their flight plans based on a meteorology and contrail forecast that could be 12–24 h old, then there may be greater uncertainty over the accuracy of the forecast by the time the flight reaches cruise.

Contrail climate forcing is highly concentrated on a small subset of flights: ~2% of flights account for 80% of the total $EF_{contrail}$ over six one-week periods of air traffic data over Japan [12], while ~12% of flights and ~45% of the days are responsible for 80% of the annual $EF_{contrail}$ in the North Atlantic between 2016 and 2020 [21] (see Figure 3).

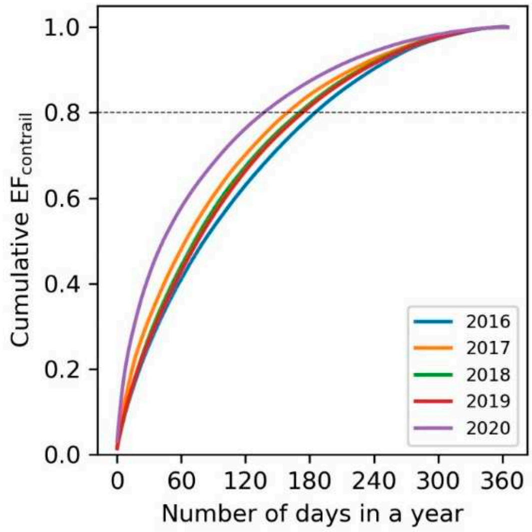

Figure 3. Cumulative density function of the annual $EF_{contrail}$ versus the number of days in a year that accounts for the proportion of $EF_{contrail}$ over the North Atlantic (Shanwick and Gander FIRs) between 2016 and 2020 (Derived using data provided by Teoh et al. [21]).

For transatlantic flights, strongly warming contrails generally occur: (i) during the winter months; (ii) between 15:00 and 04:00 UTC; (iii) close to the tropopause at altitudes between 35,000 and 40,000 feet; (iv) above low-level clouds with high albedo; and (v) from aircraft types with a high number of nvPM particle emissions per unit distance travelled [21]. The implications of this are (i) with lower traffic levels in winter, aircraft operator and ANSP support teams are likely to be better able to manage contrail-minimization requests; (ii) the early morning strong warming-contrail period coincides with an eastbound peak flow using the OTS prepared by NAVCANADA, which may be less flexible at that time, while the late afternoon strong warming-contrail period coincides with a more even flow of traffic east/west bound, which is likely to be more flexible as a result; and (iii) and (iv) where candidate flights can be prioritized in advance according to aircraft types with high nvPM emissions.

The support teams referred to above include aircraft operator dispatch/flight operations, as well as ANSP airspace capacity management, operations, and network management. Each team has their well established and complementary roles in supporting the delivery of normal services, as well as facilitating special requests such as contrail minimization as outlined in Table 1 and Section 4.

Given the seasonal effects, it would be prudent to organize a trial over a 12 month period, although this won't account for longer multiannual variation [52], potentially commencing with the winter schedule. As the trial is likely to only involve a small number of aircraft operators, only a subset of Shanwick flights would be included, so no counterfactual is required and therefore it will not be necessary to intervene on alternate days to minimize contrails, which was the case for the MUAC trial. The outcome of the intervention with the candidate flights can instead be compared to similar nearby flights which will not be in the trial.

3.5. Validation

The fifth factor is the validation requirements of the trial. Validation of contrail forecasts may be difficult with only a small number of aircraft operators, or over a short trial period. However, options do exist and include: (i) flight crew observations from nearby aircraft; (ii) satellite observations, e.g., via NASA Moderate Resolution Imaging Spectroradiometer [53]; (iii) ground observations; (iv) or in situ observations and measurements [24,54,55]. Options (i, ii and iii) are already feasible and would not require significant investment in new airborne equipment, although these would complement (iv). For (iv), an aircraft should ideally be equipped with rear-facing cameras (to see whether a contrail forms), a high-quality humidity sensor, an upward- and downward-looking radiometer to measure incoming and outgoing solar and infrared irradiances, used with meteorological forecasts and a contrail model [27,54] to determine if the contrails formed are warming or cooling [55].

While the MUAC trial incorporated a control by targeting interventions on alternate days only, given the likely small-scale nature of an oceanic trial, it may be possible to use nearby flights, e.g., parallel or following, outside of the trial as the control group with a focus on near-real-time validation. Post-operation analysis should be undertaken as outlined in similar studies [21,52].

The aim of the trial could also consider whether the approach should include contrail minimization and formation, in equal amounts, in order to review the accuracy of the forecast predictions. Recognizing that it is not possible to prove a negative, the trial could instead show that it is possible to create and avoid a persistent contrail on demand.

Ultimately the ambition and scope of the trial will determine the validation requirements.

4. ATM Strategies for Minimizing Contrails in the North Atlantic in a Trial

ATM over the North Atlantic has mainly relied on the OTS to maintain safe separation of aircraft on long routes where aircraft tend to maintain a stable speed, flight level (FL), and headings. A set of eastbound and westbound tracks are published daily by NAVCANADA and NATS, respectively [56]. The publication of the tracks allows aircraft operators to then flight-plan their preferred trajectory [57]. Although NATS is responsible for ATM in the Shanwick FIR, it designs the OTS for the full westbound oceanic crossing, including the Gander FIR. While the OTS is evolving with improved surveillance of oceanic routes [58] and is expected to shrink in the coming years leading to proportionally less aircraft using it, any contrail-minimizing strategy will need to respect the principles of the OTS and the safety requirements of the service provided to all aircraft.

4.1. Existing Approach, Assumptions and Constraints for Flight Planning in Shanwick FIR

For all ATM strategies outlined below, it is assumed that some or all of the following apply for a trial:

- The individual flight is passing through Shanwick and Gander FIRs, e.g., from Europe towards the east coast of North America or vice versa;
- The aircraft operator is responsible for coordinating with their flight-plan, meteorological, and contrail-forecast providers;
- The flight is timed to coincide either with (rather than against) the peak flow of traffic or outside of any peak flow, to minimize operational disruption to other aircraft (see Sections 3.2 and 4.2–4.5);
- Unlike the MUAC trial, both horizontal and vertical changes to the flight plan are considered;
- The aircraft operator advises the ANSP of the likely flight plan on the day prior to flight (D-1), in a format that has been agreed on by all parties, to allow for advance coordination and planning by support teams;
- On the day of the flight, the flight plan is submitted by the aircraft operator as normal with an updated expected arrival time at the oceanic entry point (also known as the gate).

Within the context of the above assumptions, four ATM strategies are outlined below which could be used to minimize persistent-warming-contrail formation. The choice of option will be influenced by the number of flights involved in the trial at any one time (and overall), the length of the trial, and resources. The first three ATM strategies are readily deployable, i.e., they have already been used by ANSPs and aircraft operators for individual flights for various purposes. They can be tailored to allow for a contrail-minimization trial once the requirements have been identified and agreed on by all stakeholders. The fourth ATM strategy will require development as it has not been tested before.

Each strategy relies on the underlying technology and ATC procedures in use in Shanwick (and Gander) FIR [59]. Typically, aircraft operators send a preferred route message (PRM) to the ANSP responsible for track publication at D-1, i.e., indicating where they are likely to flight-plan their flights the following day. The ANSP will plot a track, or tracks, based on weather, PRMs, and other factors, e.g., airspace restrictions due to military activity. The tracks are subsequently published and aircraft operators use them to flight-plan routes for individual aircraft. On the day of the flight, once airborne, an estimated time of arrival at the gate is shared with the relevant ANSP which then processes the flight plan through various internal stages from uncleared to cleared. A provisional clearance status 'protects' the trajectory in the ATM system so that potential conflicts are identified in advance. Standard practice for westbound aircraft is for the flight crew to contact Shanwick via datalink or very high frequency radio with an estimated time of arrival at the gate and request for clearance, typically 30–90 min in advance. Approval of the trajectory is then given to the aircraft and the profile becomes fully cleared.

4.2. Tactical Contrail Minimization

Tactical contrail avoidance follows current processes as normal, other than including a note in the flight plan advising the ANSP that the flight crew may request tactical FL and/or route re-clearances to minimize persistent warming contrails (assuming the aircraft operator has access to contrail forecasts). No specific pre-coordination is necessary with the ANSP. Inflight ATC requests made by the flight crew will be considered as normal, taking account of traffic levels and other operational factors. It may not be possible to manage a full re-clearance request.

A supplementary approach for tactical contrail minimization may also be possible in future, similar to the MUAC trial. If ANSPs are provided with access to contrail prediction or ISSR forecasts, then they could advise the flight crew on re-clearances to avoid these areas. However, this would need changes to the underlying technology and ATC procedures, including the Controller-Pilot Data Link Communication message being set to incorporate specific clearance dialogue to be included, alongside the support of the aircraft operator.

4.3. Alternate Flight Profiles

Alternate profiles can be prepared and may be protected if there is uncertainty on the contrail forecast. This would allow for a primary and secondary profile preference up to the initial clearance request being made, as only one would be cleared for the flight. This option allows for the blocking of a small number of flight levels for the cleared profile, e.g., two flight levels above the cleared profile, a step climb, or even a parallel route offset by a degree.

This strategy requires coordination by the ANSP and aircraft operator by D-1 (at the latest) to agree the estimated time of arrival, provisional flight profile, and ATC procedure. Further refinement of the requested profile may be possible, up to an agreed time before departure, based on the most recent contrail forecast.

After departure, the contrail forecast would be rerun; the flight profile can then be finalized and the clearance request is made prior to reaching the gate. With the flight level block, there may be implications for other aircraft who might have otherwise sought a climb to or through those flight levels. A similar process was used for the AIRE 2 demonstration flights, e.g., TOPFLIGHT [60].

This ATM strategy could be used for the pre-tactical or hybrid intervention types described in Table 1. With the pre-tactical intervention, the contrail-minimizing flight plan is prepared in advance with the contrail forecast available at that time. With the hybrid intervention, alternate profiles can be considered and finalized based on a rerun contrail forecast.

4.4. Reservation (Route or Area)

The reservation option allows for a route (or area of airspace) to be reserved, with dimensions to be agreed upon in advance between the aircraft operator and ANSP. Reservations allow for a block of airspace of pre-defined dimensions (vertical, lateral, and time) to be protected for sole use by an aircraft. For example, a reservation may extend from FL360 to FL380 vertically and 60 nautical miles laterally and for certain periods of time, allowing for multiple tactical profile adjustments by the flight crew. These adjustments would not need tactical approval from ATC as long as the aircraft remained within the pre-agreed reservation. A similar process was used for the Airbus fello'fly demonstrator flights in 2021 [61]. This strategy requires coordination by the ANSP and aircraft operator by D-1 at the latest.

Depending on the size of the reservation, other aircraft may not obtain their preferred route, or other flights which might have sought a climb to or through those flight levels or adjacent tracks would be affected. Therefore, this is a very restrictive approach in terms of airspace capacity for the wider North Atlantic and ANSP approval may be time- or level-constrained to avoid significantly disrupting operations at certain times or flight levels.

This ATM strategy could be used for the pre-tactical or hybrid intervention types described in Table 1. With the pre-tactical intervention, the route reservation could be defined broadly if low traffic was expected and the accuracy of the contrail forecast might not be as critical in advance. If traffic was high, then the hybrid intervention may be more appropriate in order to rerun the contrail forecast and limit the reservation, allowing reasonable flexibility for the flight crew, while minimizing disruption for other aircraft.

The impact of reduced capacity may prohibit this strategy being rolled out on a large scale with existing technology and ATC procedures. There are also system constraints on the number of reservations that can be handled, and the complexities inherent in managing these from an ANSP perspective mean that this strategy would be better suited to quieter periods.

4.5. Minimal Warming Contrail OTS Track

This strategy relies on the existing OTS process to create a specific track, or tracks, to minimize persistent-warming-contrail formation. At D-1, the ANSP would plot a track, or tracks, based on weather and contrail forecasts, a preferred route message (or provisional flight plan) from the aircraft operator, submitted by 18:00 UTC for the westbound track preparation process. The specific track would be published as part of the conventional tracks and potentially be available for use by any aircraft operator.

The minimal contrail track has the advantage of creating a dedicated and flight-plannable trajectory for any aircraft, without impacting the core flow of traffic on the OTS if both sets of tracks are parallel, or at least do not interact. For example, at present eastbound New York and Gander tracks frequently cross, but they are separated by different flight levels. If the contrail forecast suggests the minimal warming track would interact with the conventional OTS, then it would need to be deconflicted at the time of preparation, especially if multiple flight-level changes were required. Only a trial with operational input from multiple stakeholders will be able to determine to what extent the potential conflict is likely and to explore the mitigation options. Depending on the scope of the trial, this planning phase would need to be carefully considered in advance as the OTS has not been used in this manner before.

This strategy is a pre-tactical one as once published at D-1, the track is not flexible. While tactical changes by aircraft are possible between track levels, horizontal changes between tracks may be operationally challenging and would lead to increased workload for flight crew and air traffic controllers.

The minimal contrail OTS track strategy is unlikely to be as operationally disruptive as the reservation option, but would require more planning and coordination pre-tactically by the ANSP, aircraft operator, and contrail forecaster.

This strategy would require the ANSP to have full visibility of the meteorological and contrail forecast to design both the conventional OTS and a minimal warming-contrail track.

Were a more extensive climate-mitigation strategy to be sought by regulators [10] or the industry, the likely approach would be for the ANSP to design the majority of tracks to avoid contrails or facilitate climate minimum-impact trajectories [39].

5. Discussion

The challenges involved in setting up a contrail-minimizing trial will be significant. The following section highlights these in order of difficulty, aside from the safe operation of the ATM strategies.

5.1. Policy, Funding and Stakeholder Engagement

While aviation's non-CO_2 emission impacts have been under investigation for over two decades, there has been little interest from policymakers in understanding this challenge, possibly because the aeropolitics linked to what has been agreed on regarding the industry's CO_2 emissions have been so difficult to date [62]. While basic research on the topic has been funded, despite the lack of a coherent policy objective at international (e.g., ICAO) or national levels, some individual industry stakeholders have taken the initiative. All aviation stakeholders should be encouraged to embrace the challenge and help engage in identifying a solution; without them, a successful trial will be impossible.

5.2. Contrail Forecasts

A concern for all four of the ATM strategies described above is the accuracy and stability of the meteorological and contrail forecast, especially at D-1 and leading up to the flight (see Figure 2). While some meteorological forecasters can predict contrail formation, many lack the capacity, capability, and mandate to provide this service to the aviation industry. Therefore the aviation industry must make a request of meteorological agencies to provide this service. However, it will take time and investment to improve the accuracy, stability, and frequency of contrail forecasting.

There is a particular challenge for aircraft operators and ANSPs to finalize a track or flight plan for the next day, when relying on a forecast that might already be 12 h old at the time of preparation. In the interim, one approach would be for the aircraft operator to finalize the horizontal element of the flight plan (or potentially for the ANSP to finalize the horizontal path of the contrail-minimizing OTS track) and tactically optimize the vertical profile of the flight plan on the day based on the most up-to-date forecast.

5.3. Validation

Validation of the trial, including the contrail forecast, is a key challenge. The ambition of the trial, including agreement on its aims by the stakeholders, will frame the validation requirement. While testing the feasibility of safely managing a contrail-minimization strategy is important, the trial must be able to show that it can forecast, identify, and minimize persistent warming contrails.

5.4. Additional CO_2 Emissions

A concern typically raised with deploying a persistent-warming-contrail-minimizing strategy is that it could lead to longer routes as a result of the additional distance to fly around or above/below the ISSR. However, the current approach to flight planning prioritizes the minimization of cost [3,63], which does not merely involve minimizing fuel/CO_2 emissions. These costs include finance, fuel, staffing, ATC/airport charges, and others. All things being equal, the current convention is for aircraft operators to fly longer routes to minimize domestic ATC charges. Even with a fixed oceanic ATC charge in place, aircraft operators are so sensitive to ATC charges that they will file different routes through European airspace to minimize these costs [64], which differ between states.

In a contrail-minimizing trial, aircraft operators would only burn more fuel in avoiding contrails if they filed a minimum fuel route in the first place. If that were the case, then 'Poll's rule' states that if X% of a route is through an ISSR and if the Mach number is constant, then the additional trip fuel required for a temporary 3000 ft change in altitude to avoid the ISSR is about 0.025 X% [42], which should help alleviate the initial concerns. Aircraft operators will continue to be incentivized to opt for longer routes, in order to minimize ATC charges, until agreement is reached on common or harmonized enroute ATC charges by ANSPs and regulators [65].

In adopting a minimum-warming-contrail strategy, an aircraft operator should ideally aim to fly a minimum-climate-impact route, i.e., the initial flight plan would be a trajectory which minimizes CO_2 emissions, not total costs. Applying any one of the ATM strategies above may increase the route length (and CO_2 emissions) beyond the initial minimum CO_2 route, but the increase would be small, especially if the trial focused on only targeting persistent warming contrails. The increase could even be capped, by design, at the amount equivalent to the conventional minimum cost flight plan, thereby allowing for a no-regrets approach.

We expect results from contrail-avoidance demonstrator flights currently underway to show that aircraft operators can reduce CO_2 emissions and avoid contrail formation if they are prepared to fly the minimum-climate-impact route, irrespective of the increase in total costs arising from flying through some FIRs with higher ATC route charges. This should be kept under close review in a trial. Any marginal additional costs incurred as a result of flying through airspace with higher enroute ATC charges could either be passed through to passengers or be funded by the trial.

Greater transparency on flight planning, minimum-cost versus minimum-CO_2-emission routing (and minimum-climate-impact routing) in a trial would also help alleviate concerns about the tradeoff between minimizing contrails and the potential for extra fuel burn from longer routes.

5.5. Information Sharing and Decision-Making

Optimizing the flow and sharing of information between the individual stakeholders, including the assumptions and decision making used by each, is likely to be a challenge given commercial restrictions. Based on the experience of contrail-avoidance trials to date, the timing and collaborative decision making linked to contrail forecasts and flight planning is absolutely critical. It is expected that any trial would seek to improve the awareness of, and dependencies on, operationally relevant information for all stakeholders.

A related challenge will be reaching an agreement to provide open-access data and documentation by all stakeholders. This will be important for validation and peer review.

5.6. Governance

While minimizing persistent warming contrails is unlikely to be described as geoengineering [66], any large-scale trial should be mindful of unintended consequences. There are limited parallels to draw from, so the project will have to review and adopt governance best practice.

6. Recommendations

The design principles, ATM strategies, and individual challenges outlined in this paper have been prepared to inform the development of future contrail-minimizing trials. These should be tested as part of a real operational trial to better understand the pros/cons and implications for all stakeholders.

We recommend a one-year trial in the North Atlantic, with the support of relevant ANSPs, a representative sample of aircraft operators (and fleet mix), a meteorological agency and contrail forecaster, and a flight-planning provider to test and validate a concept of operations for persistent-warming-contrail minimization. The focus should be on optimizing pre-tactical decision making by aviation stakeholders.

We also recommend, either as part of this trial or in advance, work to be undertaken to assess how the OTS could be adapted to include a specific track which seeks to minimize persistent warming contrails. This should specifically examine how the conventional tracks and a minimal contrail track might interact and be deconflicted using realistic scenarios and input from relevant stakeholders.

From a scientific viewpoint, we further recommend meteorological agencies prioritize the improvement of humidity prediction at contrail-forming flight levels in the upper troposphere.

Policymakers are strongly encouraged to fund continued research on these topics, including a large-scale trial, and the aviation industry is encouraged to actively support and engage in such a trial.

Dedicated to Dr. John Green (1937–2022).

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Abbreviations

ANSP	air navigation service provider
ATC	air traffic control
ATM	air traffic management
ECMWF	European Centre for Medium-range Weather Forecast
ERF	effective radiative forcing
FIR	flight information region
FL	flight level
ICAO	International Civil Aviation Organization
ISSR	ice-supersaturated region
MUAC	Maastricht Upper Area Control Center
nvPM	non-volatile particulate matter
OTS	organized track structure
PRM	preferred route message
RF	radiative forcing

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