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End-to-end operational trial of contrail avoidance on transatlantic commercial flights

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Abstract

Aircraft contrails can exert a substantial warming effect on climate, and avoiding their formation through changes in trajectory has emerged as a potential aviation climate mitigation strategy. However, operational evidence of its effectiveness and practicality remains limited. Here we report an end-to-end contrail avoidance trial conducted by Air France within the CICONIA project between February and April 2026. Among 4,296 transatlantic flights processed, 245 were identified as candidates and 130 were successfully rerouted using vertical re-optimisation of the original flight paths. The contrail climate-impact reduction was estimated to be 28,670 tCO_2e based on operational weather forecasts and optimised trajectories using a contrail impact model. Accounting for updated meteorological information and the trajectories actually flown resulted in a reduction of 22,500 tCO_2e estimated from the same modelling framework. This benefit was achieved with approximately 130 tonnes of additional fuel, corresponding to 1.83% additional fuel consumption on average for rerouted flights. The trial demonstrates that contrail avoidance can be integrated into long-haul airline operations and could deliver substantial climate benefits, while highlighting the importance of managing weather forecast uncertainty and operational constraints, reducing the fuel penalty, increasing effectiveness, and achieving further automation for scaling.

Introduction

Aviation contributes to global warming through several pathways. It is responsible for roughly 2.5% of global anthropogenic CO_2 emissions each year, but its overall warming effect is substantially greater when non-CO_2 effects are taken into account[1]. Among these, contrail cirrus represent the dominant contribution and are estimated to exert an effective radiative forcing of a similar magnitude to that associated with cumulative aviation CO_2 emissions[1-3].

Aircraft contrails are line-shaped clouds formed when water vapour from aircraft exhaust mixes with cold and humid air at cruising altitude. Contrails that form within ice-supersaturated regions (ISSR) are of particular climatic relevance because they can persist, spread over large areas,

and eventually evolve into contrail cirrus. Contrail cirrus affects the Earth's radiation balance in opposing ways, warming the climate through the absorption and re-emission of terrestrial infrared radiation and cooling it through the reflection of solar radiation. While their effects vary significantly according to the aircraft characteristics, fuel properties, meteorological and environmental conditions, contrails generally warm the climate system, especially if they occur predominantly during nighttime. Globally, a small fraction of flights, on the order of 2-3%, has been estimated to account for roughly 80% of the effective radiative forcing associated with contrail cirrus worldwide[3]. However, at the regional and seasonal scale, such as for wintertime transatlantic traffic, a substantially larger proportion of flights may contribute to warOn the subset this represents a normalised reduction of 220.2 kgCO2e/kg fuel or 69.7 kgCO2e/kgCO2

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ming the climate system. The importance of aviation non-CO_2 effects in general, and that of contrails in particular, is also recognised by the implementation of a dedicated Monitoring, Reporting, and Verification (MRV) scheme at the European level, effective since January 2025 (ref. 4).

In parallel a range of mitigation approaches has been proposed to reduce the climate impact of contrails, including the use of alternative fuels and the rerouting of aircraft to avoid contrail-forming regions. (Here the term “rerouting” refers to a deliberate change in flight trajectory for avoiding contrails, rather than an airport diversion.) Although lateral rerouting can be beneficial in some situations, vertical flight-level adjustment has been recognised as a promising mitigation option for over two decades[5-7]. Contrail avoidance is an attractive mitigation option because, unlike many other measures in aviation, it could now be implemented on a timescale of less than a decade, and would deliver rapid climate benefits given the short-lived nature of contrails[8-9].

Various studies have demonstrated the potential climate benefits of contrail avoidance and the relatively low associated additional fuel cost. Many past studies[6,10,11] have relied solely on simulations, leaving open questions about operational feasibility and implementation constraints. A small number of trials were conducted in recent years to further assess the practicality and climate benefits of contrail avoidance in real-world conditions. The first-ever trial took place in the Maastricht Upper Area Control in 2021 and consisted in deviating air traffic every other day by changing the flight altitude by up to 2000 feet up or down if the formation of persistent contrails was predicted[7]. Rerouted flights formed significantly fewer contrails than non-rerouted flights, even though the analysis was based on only 23 flights for which rerouting was implemented under forecast persistent-contrail conditions. The additional fuel consumption was not assessed. Other trials were conducted on a voluntary basis by some airlines, including American Airlines (AA) in 2023 (ref. 12) and 2025 (ref. 13), and TUIfly, Lufthansa, Condor and DHL[14,15] as part of the TF100 flight trial. With the exception of the 2025 AA trial[13] that did not detect a statistically significant difference in fuel usage, previous trials noted increases in fuel consumption in the range of 1.5 to 2.8% for rerouted flights[12,16]. These trials have generally relied on unpaired control and treatment groups, which limits their ability to robustly estimate

changes in fuel consumption. In particular, flights that are delayed are often excluded from rerouting but they are retained in the control group. Because delayed flights may subsequently fly at higher speeds to recover some of the delay, their fuel consumption can be higher than that of otherwise comparable flights. Including such flights in the control group therefore inflates the estimated baseline fuel burn and can lead to an underestimate of the additional fuel consumption associated with rerouting. Finally it should be noted that while earlier trials[7,12] aimed at avoiding contrail formation altogether, later trials[13,14] used flight planning systems that penalise, but not necessarily eliminate, contrail warming effects through a contrail-optimised trajectory.

As part of the CICONIA project, Air France conducted an end-to-end contrail avoidance trial whose primary objective was to assess and address practical implementation challenges across the full workflow, from weather forecasts and flight planning to airline operations and flight execution. Specific objectives were to test contrail avoidance in the vertical plane, define procedures that are robust against operational constraints, and maximise engagement from the flight dispatch teams and crews. The trial should thus be viewed as a pilot-scale demonstration that explicitly incorporates both the human and technological dimensions within the complexity of the air transportation system. A unique feature of this trial is the operational release of both a cost-optimal and a cost–climate-optimal flight plan, which demonstrates their flyability while also enabling a direct comparison between the two flight plans, especially in terms of fuel consumption. This distinguishes this trial from previous trials[13] and provides a first benchmark against which future navigational trials can assess and improve the cost and efficiency of contrail avoidance.

The trial was conducted from 2 February to 12 April 2026, after an intensive planning phase and two shadow trials that ran in succession from June 2025 until January 2026. Flights considered for rerouting comprised inbound and outbound services between the Paris airports (Charles de Gaulle and Orly) and destinations in Canada, the United States, Mexico and the Caribbean (Fig. S1). Flight plans minimising contrail climate impact were generated independently by two providers, Estuaire and Klima, using a vertical-only flight-level re-optimisation of the original flight path (see Methods). The optimised trajectories were then submitted to the airline's dispatch team and, when operationally feasible, reintegrated into Air France flight planning system to verify their operational compatibility, flyability and safety. Following dispatcher’s review, the trajectories were proposed to the flight crew, who retained the final decision to either accept the climate-optimised flight plan or revert to the original flight plan (see Fig. 1 for the full operational workflow).

It was identified from the outset that the success of the trial would depend critically on its uptake by the relevant operational teams at Air France. The engagement of dispatchers and flight crews was built around three complementary principles: communication, transparency, and flexibility (see Fig. 2 for a review of the activities). Communication played a central role in raising awareness and fostering acceptance of contrail avoidance operations. All Air France pilots complete a regulatory training, which last year included a dedicated module on aviation contrails and their climate impact. The initiative was also presented company-wide by the CEO at the beginning of the year, and, prior to the start of the operational trial, pilots received dedicated

written and video communications explaining the objectives and procedures of the experiment. Two seminars were organised with dispatchers to explain the motivation for the trial and the process and to seek feedback on its implementation. Transparency was ensured by providing both dispatchers and flight crews with comprehensive information before every proposed rerouting. Approximately three hours before departure, each candidate flight for rerouting was accompanied by a PDF file summarising the forecast contrail-forming regions, the proposed alternative trajectory, and its expected impacts on flight time, fuel consumption, and climate benefit, allowing informed operational decisions. To maintain trust and operational flexibility throughout the trial, dispatchers were also provided with a "switch" enabling recommendations to be suspended during highly constrained operational situations, such as severe weather or international crises; this option was exercised only once during the campaign. Finally, maintaining a high standard of rerouting recommendations was essential for sustaining engagement. Several months of iterative development refined the proposed trajectories to eliminate undesirable features such as unnecessary or too frequent level changes. The resulting high-quality rerouting solutions, developed jointly by Klima and Estuaire, progressively strengthened the confidence of Air France dispatchers and flight crews in implementing and operating these climate-optimised trajectories.

Results

A total of 4296 flights were processed during the 2.5-month trial period. The criteria for candidate flights were slightly adjusted during the course of the trial so as to aim for at least 100 rerouted flights over the period (see Methods). This resulted in 245 candidate flights, among which 130 were successfully rerouted (Fig. 3a). The acceptance rate of proposed trajectories was 53% when considering the full operational chain from dispatch evaluation to execution by the flight crew (Fig. 3b).

At the dispatch stage, 64% of candidate trajectories were accepted for operational implementation. The acceptance rate shows a gradual decline as the trial progressed, which we interpret as reflecting increasing weariness among the teams involved, possibly due to the manual process of re-issuing operational flight plan (OFPs). Figure S3 summarises the documented reasons why the dispatch team did not follow up on a subset of candidate flights. A reason was recorded for 35 of the 89 dispatch non-applications. In some cases, route changes occurred between transmission of the recommendation and its implementation, rendering the recommendation obsolete. High dispatcher workload, particularly following the outbreak of the 2026 Iran war (that started on Feb 28, 2026) and the associated repatriation operations, temporarily constrained the capacity to process contrail-avoidance recommendations. In addition, each rerouted trajectory had to be recalculated and released through the existing flight planning tool, which occasionally resulted in the system rejecting the proposed trajectory. Other documented reasons included payload limitations resulting from the additional fuel requirements associated with rerouting, turbulence along the rerouted trajectory, and flight delays or cancellations. Altogether most documented non-applications resulted from operational changes or implementation workload. These observations highlight the operational constraints that can

affect the implementation of contrail-avoidance recommendations even when a candidate flight has been identified.

At the flight stage, acceptance was generally high, with only 11% of candidate flights not being implemented due to a pilot decision (or 17% when calculated relative to candidate flights approved by dispatch and subsequently presented to the pilots). Pilot feedback was collected through an optional questionnaire and is presented in Fig. 4. A single feedback may cover several topics, and 91 feedback entries were collected in total, with some feedback being purely factual. Figure S4 summarises the feedback collected, with a response rate of 70% across all flown avoidance flights, which indicates a good understanding of the rationale behind the proposed changes and strong engagement with the trial. Most feedback related to operational feasibility or confidence in the climate rationale. In some cases, actual flight conditions prevented the recommended trajectory from being fully implemented, highlighting the importance of flexibility in operational deployment. Pilots also emphasised the need for clear evidence that the expected climate benefit justified the associated fuel penalty. This feedback could be interpreted either as a request for evidence of the benefit for the individual flight or as confidence in the expected benefit of the approach on average across the trial. In both cases, the level of evidence required to support confidence in the climate benefit remains an important aspect to be further investigated and communicated. Finally, feedback highlighted the value of clear, concise information and simple flight-level changes to minimise additional workload during flight operations.

Deviations between the accepted rerouted flight plans and the trajectories actually flown were primarily associated with operational constraints encountered during the flight. Two main factors explained these deviations: i) air traffic control (ATC) constraints limited the ability of crews to return to the optimal flight level when appropriate and ii) the presence of turbulence also prevented some planned altitude changes. In the most significant case observed during the trial, an aircraft remained 4000 ft below the optimised altitude for approximately 1500 nautical miles due to ATC restrictions, resulting in 600 kg of additional fuel burn.

Overall, the trial indicated that contrail avoidance trajectories can be well accommodated within routine airline operations if they are supported by coordination among flight planning teams, dispatchers, and crews. These findings suggest that the practical implementation of contrail avoidance depends not only on the quality of the optimised trajectories, but also on their integration into existing operational workflows and decision-making processes. Moving beyond a trial, however, would require further automation and deeper integration of the tools.

Figure 5 illustrates an example of the trajectory modifications considered during the trial. The re-optimised trajectory departed from the original flight plan through vertical adjustments designed to avoid regions identified as favourable for persistent contrail formation. In this case, the re-optimised trajectory avoided two contrail-prone regions (labelled A and B), while remaining within the operational constraints defined for the trial. The trajectory actually flown by the aircraft differed from the optimised trajectory because the flight crew retained final authority over trajectory changes. In particular, the planned climb was not performed due to the presence

of clear-air turbulence, leading the aircraft to cross a small contrail-prone region that was neither on the original nor on the re-optimised flight plan (labelled C). This example highlights the importance of integrating meteorological information, optimisation algorithms and operational decision-making when assessing the real-world implementation of contrail avoidance strategies.

The aggregated mitigation potentials are shown in Fig. 6 for the 121 rerouted flights (out of 130) for which complete contrail impact estimates were available. Based on the weather forecasts available at the time of flight planning, the original trajectories were estimated to generate a total contrail climate impact of 39,551 tCO_2e (all CO_2e are computed according to the EGWP100 metric, see Methods). The climate optimised trajectories of the providers with the operational weather forecast at the time exhibit a planned reduction of 27,082 tCO_2e (28,670 tCO_2e on the full dataset) or 68.5% reduction in contrail climate impact.

The real contrail impact reduction however is lower. When retrospectively recalculating the contrail impact of the original OFPs using updated meteorological information, and recalculating the climate optimal OFPs with updated numerical weather prediction (NWP) data as well, the difference (the mitigation potential) between the two is reduced by 6,349 tCO_2e, or 16.1%. The remaining climate benefit is thus 20,733 tCO_2e. The ~16% reduction in benefit between initial and updated estimates for the rerouted trajectories reflects the sensitivity of contrail avoidance opportunities to meteorological forecast uncertainty and the fact that ice-supersaturated regions cover only a small fraction of the airspace.

Finally, the contrail impacts were calculated along the actual trajectories flown by the aircraft using reconstructed ADS-B trajectories. These calculations resulted in a final mitigation of 21,080 tCO_2eq, corresponding to a 53.3% of the total mitigation potential for those flights. The close agreement between the updated rerouted estimates and the impacts calculated from the actual trajectories indicates that the majority of the optimised climate benefit was retained during operational execution, despite deviations from the optimised flight paths. When computed against the latest weather forecast or the reanalysis, the total contrail savings, estimated to be 21,080 tCO_2e can be extrapolated to ~22,500 tCO_2e when rescaled to the 130 rerouted flights. Fig. S4 shows the differences in contrail estimates on a flight-by-flight basis.

The additional direct fuel consumption associated with the rerouting strategy was quantified for the flights successfully rerouted during the trial (see Methods). Across the 128 flights for which OFP fuel data are available, the implementation of contrail avoidance trajectories resulted in an additional fuel burn of 128 tonnes, corresponding to an additional direct CO_2 emission of approximately 404 tonnes (using a CO_2 emission factor of 3.159 kg CO_2 / kg fuel).

The ratio of avoided contrail climate impact to additional fuel burn amounts to 186.5 $kgCO_2e/kg$. Using the same emission factor as before, this means that each additional kilogram of CO_2 emitted was associated with the avoidance of 59 $kgCO_2e$ of contrail climate impact. These values illustrate the large potential climate leverage of contrail avoidance compared with the direct CO_2 penalty associated with small trajectory adjustments, while highlighting the

importance of accurately accounting for both CO_2 and non-CO_2 effects when evaluating aviation climate mitigation options.

Discussion

Figure 7 shows that the reduction in climate impact is only weakly related to the additional fuel consumption on a flight-by-flight basis. This weak relationship reflects two factors. First, contrail climate impacts were recomputed using updated meteorological conditions (ERA5 reanalysis and latest ICON weather forecast) while the trajectories were optimised using the weather forecasts available at the time of flight planning. Regions favourable for contrail formation may have shifted between planning and operation. Second, the optimisation objective was not designed to maximise climate-impact reduction per unit of additional fuel consumed, but rather to target flights with the largest warming impact and contrail avoidance benefit and, in the case of Klima, to also minimise the risk of inadvertently increasing the climate impact of each individual rerouted flight.

Figure 8 shows the breakdown of the fuel overconsumption associated with contrail avoidance across the full trial. The largest contribution arises from the use of suboptimal flight levels resulting from the rerouting itself, accounting for 550 kg of additional fuel per flight on average. The second-largest contribution, at 410 kg, comes from the two-tonne additional fuel safety margin that was imposed to rerouted flights (see Methods); carrying more fuel increases aircraft mass and therefore fuel burn. A further 40 kg is due to differences between the planned and actual trajectories. This overhead is concentrated on a few flights and can be attributed to contrail avoidance to a large extent, e.g. because of the impossibility to return to a more optimal flight level after a descent. It is important to note that the fuel safety margin applies to all rerouted flights even though it is only required occasionally. Overall, contrail avoidance resulted in 1 tonne of additional fuel consumption per rerouted flight, corresponding to 1.83% of the fuel consumption of the original trajectory, or 3.16 tonnes of emitted CO_2.

Our estimates of the additional fuel induced by contrail avoidance represent an upper bound for several reasons. First the implemented vertical re-optimisation is sub-optimal because changes in flight level were restricted to waypoints, due to formatting constraints when filing flight plans with Eurocontrol. A more flexible vertical adjustment would result in small additional fuel burned. Furthermore lateral contrail-aware optimisation or a full 3D cost-climate optimisation would have been more appropriate for some candidate flights. Finally the fuel safety margin was also an upper bound. Improved coordination with ATC and a formal agreement on flight-level changes could substantially reduce safety fuel requirements and the associated additional fuel consumption. Reducing the fuel safety margin from two tonnes to one tonne appears to be a reasonable objective, which would by itself reduce the additional fuel burned by more than 200 kg. Furthermore it should be noted that some newer aircraft types may also have a broader optimal altitude range (i.e. the fuel burn curve is less sensitive to altitude change around the optimum flight level). Overall the current estimate should be regarded as a first benchmark, which future trials can refine and improve upon. It cannot, however, be extrapolated directly for higher rates of contrail avoidance or to other regions, where different airspace structures, traffic

densities, ATC constraints, and meteorological conditions may affect best practices for contrail avoidance.

Our ratio between additional fuel burn and avoided contrail impact can be translated into a rough estimate of approximately €10 per tCO_2e avoided, factoring in both fixed and operational costs associated with contrail avoidance. Again this figure should be regarded as an initial benchmark to mitigate the most impactful contrails rather than a definitive cost estimate, and should be refined as more data become available on the operational costs and climate benefits of contrail avoidance. The cost is expected to decrease as contrail avoidance strategies are improved but the marginal cost may also increase if contrail avoidance is scaled up to a larger number of flights in comparison to the small number of well targeted flights in this study.

It is interesting to compare our estimate of additional fuel burn to previous studies. Sonabend et al.[12] found an average 2% increase in fuel per adjusted flight in the continental United States in their rerouted (treatment) group compared to their control group in their trial with American Airlines. This is more than in our study, especially if we remove the fraction of additional fuel burn due to the safety margin that has not been included in the short- and medium-haul flights of the American Airlines trial. In a separate trial for eastbound transatlantic flights from the United States to Europe operated by the same airline, Sankar et al.[13] found a small and not significant difference in fuel usage of 0.3% between the rerouted and the control groups. However they needed to adjust the fuel usage by large factors to correct for a large imbalance of aircraft types between the treatment and control groups. Furthermore the treatment and control groups have experienced different weather conditions. For the first time, our study estimates the additional fuel burn on the basis of the release of two OFPs representing flyable trajectories, with the additional fuel burn calculated from the difference between the fuel requirements of the original and re-optimised trajectories. This allows us to assess the impact of the rerouting on the fuel without introducing noise from differences in the treatment and control groups. The smaller additional fuel burn compared to the continental US trial may be explained by i) a reduced fraction of the flight spent away from the optimal flight level when compared to short-haul operations, ii) some of the operational constraints limiting highly penalising avoidance in this trial, for example a maximum deviation of 4000 ft from the optimal flight level and possibly iii) the focus on warming contrails rather than contrail formation as in Ref. 12, resulting in more cost-optimal avoidance trajectories.

The observational verification of contrail climate impacts from satellite data continues to prove challenging, highlighting the limitations of current satellite observations for attributing changes in contrail occurrence and climate impact to individual avoidance interventions. In particular, the combination of limited spatial and temporal sampling, uncertainties in contrail detection and persistence, and the difficulty of linking observed contrails to specific flight trajectories makes it challenging to detect a robust climate signal from a relatively small number of interventions. In particular, geostationary satellite observations can only capture contrails that are broad and reflective enough[17]. This is a challenge for trials that aim to reduce energy forcing rather than avoid ice-supersaturated regions (ISSRs) in full, since the intended objective, which is to generate less warming contrails, is not directly observable as such. Nevertheless, our results, together with feedback received from pilots, underscore the importance of designing future

contrail-avoidance trials that enable robust observational evaluation of their climate impact from the outset.

The trial showed promising results and further demonstrated the feasibility of contrail avoidance in routine airline operations, while also highlighting areas where the approach can be improved. Future trials should be designed not only to assess operational feasibility, but also to provide robust observational evidence of the resulting climate benefit. This could be achieved by increasing the number of rerouted flights, optimising against observable outcomes, targeting conditions and regions that are particularly amenable to satellite observation, and planning for appropriate control flights and observational strategies. Such trials would strengthen the empirical evidence for the effectiveness of contrail avoidance, help identify opportunities to reduce its operational costs, and provide insight into how its climate benefits and costs evolve as deployment expands. Ultimately, this would help determine the extent to which the substantial mitigation potential demonstrated here can be realised at scale.

Methods

The operational workflow of the Air France contrail avoidance trial is shown on Fig. 1. OFPs issued by the dispatch team using their standard flight planning system were pushed automatically to the servers of the two service providers. As multiple OFPs could be issued for a same flight, the OFP was only processed once three hours before flight departure. Flights whose OFPs reached the service providers beyond the three hour limit were processed but not considered as candidates for contrail avoidance.

Two independent external trajectory optimisation providers were used for the trial for several reasons. First, Air France operational flight planning system did not include a functionality for contrail-aware trajectory optimisation. Second, we wanted a process that is as automated as possible. Third, using external providers enabled the airline to retain full control over the optimisation process and to impose a common set of operational constraints on all candidate trajectories. These constraints were designed to ensure operational acceptability and safety while limiting deviations from the original flight plan. Specifically, optimisation was restricted to vertical flight-level adjustments from the operational flight plan. Trajectories were not permitted to cruise above the original flight profile; the number of flight-level changes was minimised; each modified flight level was required to be maintained for a minimum duration, except where the original flight plan already contained a shorter segment; and the maximum altitude deviation from the original trajectory was limited to 4,000 ft. Another requirement was that flight should not exceed the block arrival time due to contrail avoidance, including in cases where it was already delayed for some other reasons. An upper limit for the additional fuel consumption was set to 5% of the initial trip fuel, although this constraint was not reached in practice. A two-tonne safety margin was included in case air traffic control would not allow the aircraft to climb up on the optimal flight level after the contrail avoidance performed at a lower flight level. It was estimated from a worst-case scenario for a long-haul flight and depends on the vertical optimisation constraints. This safety margin generated an additional fuel consumption by itself.

Two independent meteorological data sources were used during the trial, reflecting the operational configuration of the two trajectory optimisation providers. Klima used weather forecasts from the operational Integrated Forecasting System (IFS, cycle 49r1) of the European Centre for Medium-Range Weather Forecasts (ECMWF), including the hourly high-resolution forecast and the three-hourly ensemble forecasts. To assess the influence of the weather forecast errors, the calculations were repeated retrospectively using the corresponding ERA5 reanalysis once it became available. The exponential boosting humidity scaling derived from the comparison of ERA5 with In-service Aircraft for a Global Observing System (IAGOS) observations[18,19] (option ExponentialBoostWithLatitudeCorrection in pycontrails) was applied consistently to the IFS forecasts. Estuaire used the pre-operational version of the Deutscher Wetterdienst (DWD) Icosahedral Nonhydrostatic (ICON) model[18] developed as the reference NWP model for the European Monitoring, Reporting and Verification (MRV) scheme for aviation non-CO_2 effects. Using this model ensures consistency between the weather data used to plan contrail avoidance and that used to report non-CO_2 effects. No humidity scaling was applied to the ICON forecasts as its two-moment ice microphysics scheme yields a realistic statistical distribution of upper-tropospheric humidity, including ice supersaturation against in situ observations[19]. As no corresponding analysis or reanalysis is currently available for this forecast, the retrospective calculations were instead repeated using the latest forecast available at the time of the flight. The latest ECMWF HRES forecast and the Google Contrails API forecast[20] were also used post-flight to confirm the robustness of the avoidance benefits. Both ICON and IFS models generate realistic ice supersaturated regions (ISSR) compared to observations[19,21,22]. However the exact location and magnitude of ice supersaturation differ in the two weather forecasts and can also vary a little with the forecast lead time for a particular valid time in the future.

Weather forecast lead times of up to 48 hours after forecast initialization (T0 + 48 h) were considered. This horizon accounts for the operational workflow, including the delay between forecast production and availability (typically 6-9 hours, depending on the data source), the approximately 3-hour interval between flight planning and departure, the flight duration, and the 12-hour integration period used to estimate the radiative impact of contrails.

Versions 0.60.2 (Klima) and 0.54.9 (Estuaire) of the CoCiP-pycontrails model[23] were used with the following configuration: integration timestep of 5 min (Klima) and 10 min (Estuaire), maximum contrail age of 12 hours, with other parameters being nominal. The resulting contrail energy forcing was converted to CO_2-equivalent emissions using a radiative forcing-based efficacy factor of 0.42 and a 100-year absolute global warming potential (AGWP100) for CO_2 of $8.22\ 10^{-14}$ $Wm^{-2}.(kgCO_2)^{-1}.yr$, yielding EGWP100-based CO_2-equivalent emissions (tCO_2eq)[24]. We introduce the concept of a climate ratio defined as the combined climate impact of contrails and CO_2 of the flight (expressed in kg CO_2e) to that of CO_2 only (expressed in kg CO_2).

The criteria used to identify candidate flights differed somewhat between the two providers. Klima screened and re-optimised the flights using the IFS deterministic forecast, and assessed each re-optimised trajectory against the 50 members of the IFS ensemble to quantify the risk of inadvertently increasing climate impact due to uncertainties in the weather forecast. This approach corresponds to the risk-aware contrail avoidance strategy introduced in Ref. 25, which

evaluates the net climate impact of rerouting by accounting for both the change in contrail effects and the additional CO_2 emissions resulting from the modified trajectory across the forecast ensemble. Candidate flights were selected based on a minimum climate ratio of the initial flight of 2, a relative reduction of the climate ratio of 0.5 and a maximum acceptable risk of 5% of damaging the climate, which was increased to 10% during the second half of the trial period to slightly increase the number of candidate flights. Information on the climate ratio for the original and rerouted trajectories, as well as the climate risk, were communicated to the operational teams. Cooling contrails were excluded from the optimisation objective to avoid favouring additional flight level changes for an uncertain climate benefit, but they are included in the calculation of the climate ratio. Estuaire evaluated the predicted contrail impact using the ICON weather forecast and selected candidate flights with a minimum climate ratio of 1.8 and a minimum climate ratio reduction of 0.5 was employed. Candidate flights not satisfying the above-mentioned requirements on delay and flight time were also screened out by both providers.

The proposed rerouted trajectories for candidate flights were e-mailed to the dispatch team for their consideration around three hours before flight departure. When considered operationally feasible, the dispatch team would implement the new trajectory into the Air France flight planning system to assess their compatibility with operational constraints, including flyability and safety requirements. Following dispatcher review, approved candidate trajectories were presented to the flight crew, who retained final authority to either accept the optimised trajectory or operate the original flight plan. Feedbacks from the dispatch team and the crew were collected for each stage through a small questionnaire.

The contrail radiative impacts were recomputed retrospectively for both the original and rerouted flight trajectories using meteorological fields from the ERA5 reanalysis and, for Estuaire, the latest available ICON forecast at the time of the flight. These estimates are referred to as the updated estimates. It should be noted that the meteorological differences between the operational forecast and the latest available ICON forecast are expected to be smaller than those between the operational IFS forecast and the ERA5 reanalysis, because the former compares two weather forecasts issued at lead times 6 to 18 hours apart, whereas the latter compares a forecast with a posteriori atmospheric reconstruction that includes observations available a posteriori and an earlier IFS cycle. Finally, the contrail radiative impacts were also calculated for the actual flown trajectories, reconstructed from terrestrial and satellite ADS-B signal retrievals. These calculations were performed using both ERA5 reanalysis meteorological fields and the latest available ICON forecast at the time of the flight.

The additional fuel burn was estimated from the Air France flight planning system by comparing the OFP of the original and re-optimised trajectories, with equal payload but including the additional fuel including the two-tonne safety margin. To account for additional fuel burn arising from unplanned operational deviations, an average surplus of 40 kg of fuel, as calculated during operations using Quick Access Recorder (QAR) data, was subsequently added to this estimate, as these deviations are likely to have been associated, at least in part, with the implementation of contrail avoidance.

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Data availability

Contrail impacts and additional fuel consumption are available as a csv file.

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Author contributions

CP and FE led the design of the contrail avoidance strategy and the engagement with dispatchers and flight crews. AB and OB developed the contrail avoidance tool for Klima. PS and NM developed the contrail avoidance tool for Estuaire. NS, PS, AB and OB performed the data analysis. All authors contributed to the article text.

Competing interests

The authors declare the following competing interests. AB and OB are co-founders and own equity of Klima. NM is a co-founder and owns equity of Estuaire, PS holds an agreement for future equity in Estuaire.

Figures

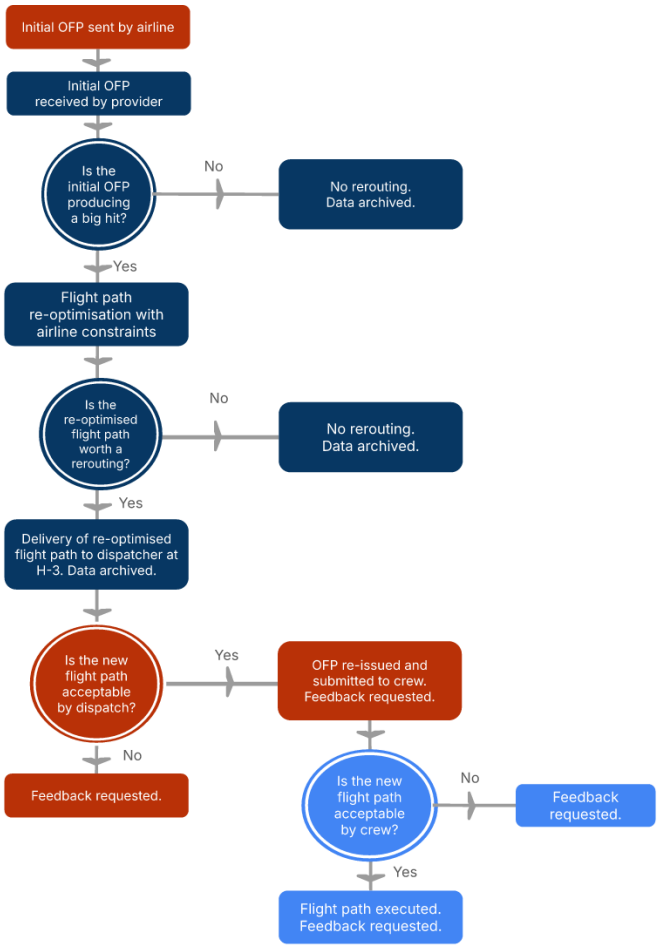


Figure 1. Operational workflow of the Air France contrail avoidance trial. The color code represents the different stakeholders: Air France dispatch team (brown color), flight re-optimisation providers (dark blue) and flight crew (light blue).

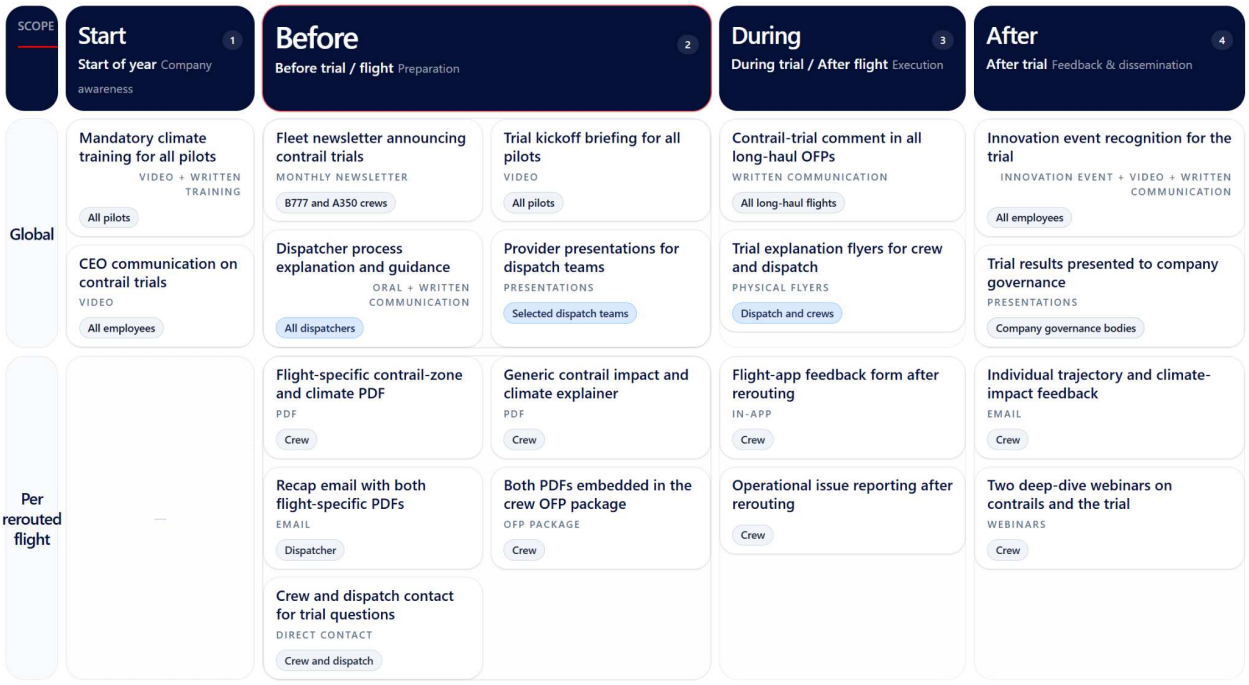


Figure 2. Schematic of contrail avoidance engagement activities conducted within Air France. A more detailed version is available as Fig. S2.

a)



b)

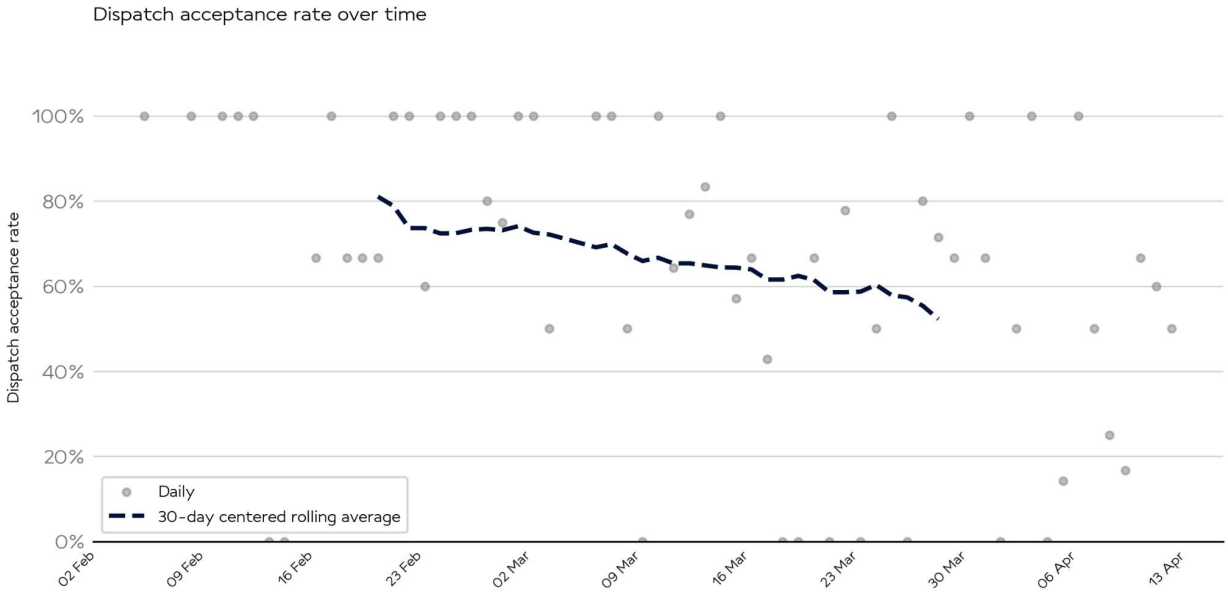


Figure 3. a) Outcome for the 245 candidate flights. b) Evolution of the combined acceptability rate from dispatch and crew during the course of the trial. The circles show the acceptance rate for each day on which candidate flights were submitted, while the dashed curve shows the 30-day running average.

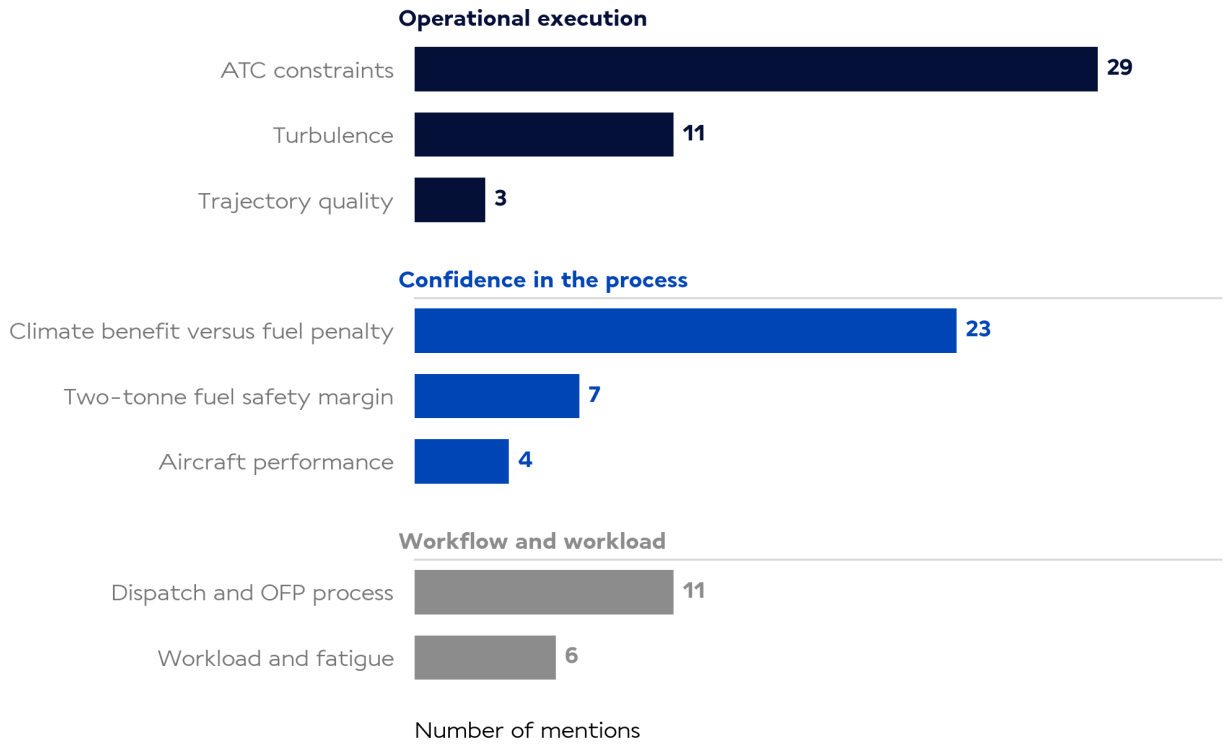


Figure 4. Analysis of pilot feedback after the rerouted flights. The feedbacks were divided into three main categories and sub-categories with the number to the right indicating the number of feedbacks for each subcategory.

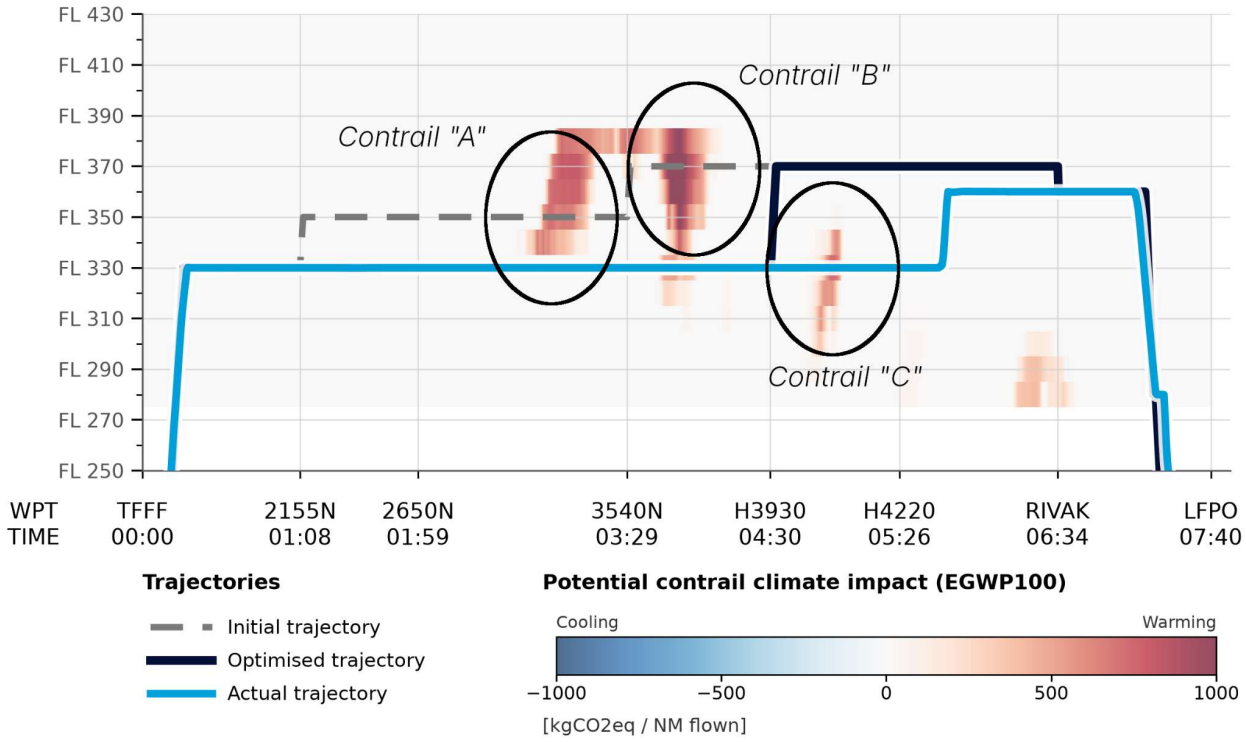


Figure 5. Input (dashed grey line), re-optimised (solid dark blue line) and actual (solid light blue line) vertical profiles of the flight trajectory for the first test rerouting. The re-optimised trajectory avoids two contrail-prone areas labelled A and B. The actual trajectory crosses a small contrail-prone area labelled C as the pilot decided not to climb up to the filed trajectory because of the presence of clear-air turbulence. The contrail climate impact is expressed in kg CO_2e per nautical mile flown with the CO_2e computed according to the 100-year efficacy-based Global Warming Potential. Waypoints along the flight trajectory are indicated.

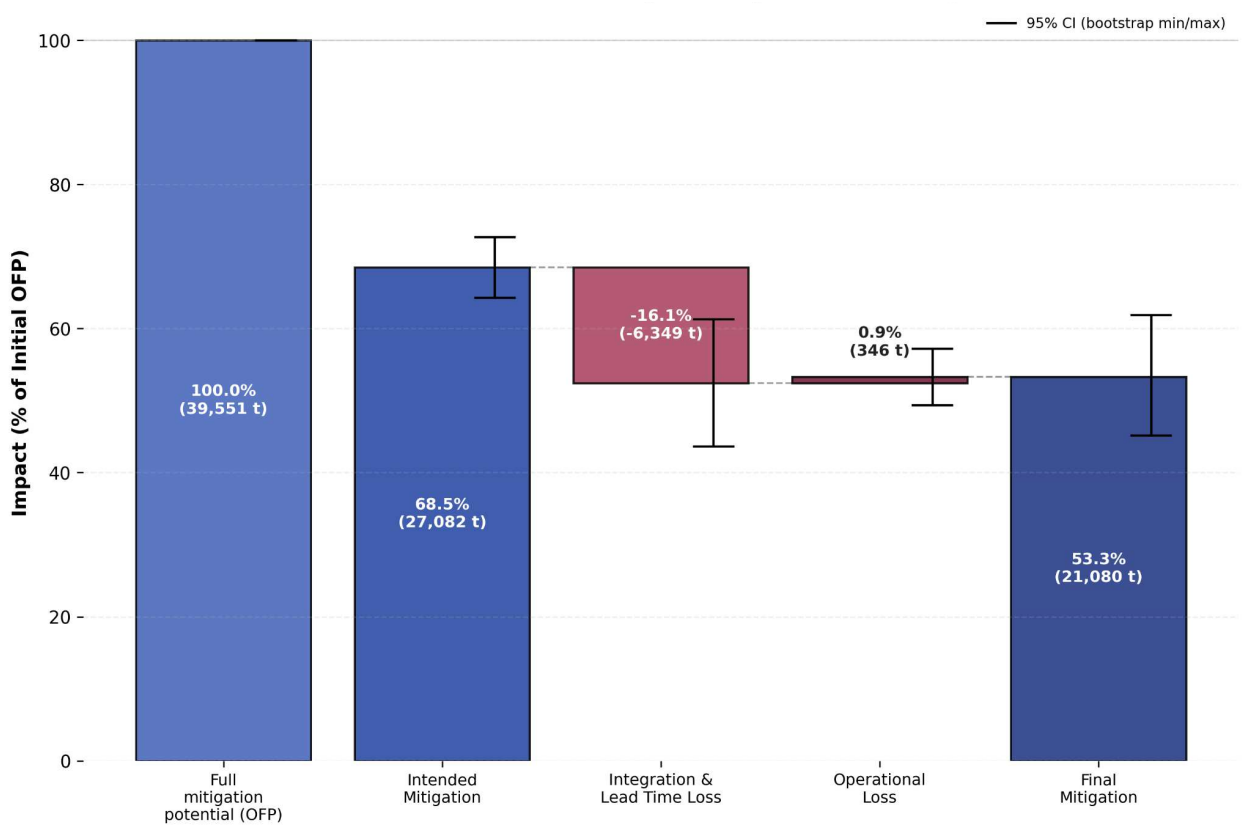


Figure 6. Contrail mitigation (in tonnes CO_2e, EGWP100 and as a percentage of maximum mitigation potential in %) at different stages of the trial. The three bars (from left to right) represent the maximum mitigation potential (estimated from the input trajectory and the weather forecast), the intended mitigation (estimated as the difference between the input and the re-optimised trajectory computed for the same weather forecast) and the final mitigation (estimated as the difference between the input and the actual (flown) trajectory and the latest forecast or reanalysis). The two bars in bordeaux color between the intended and final mitigation break down the effectiveness loss attributable i) to the integration of the new flight path in an OFP and the use of a later weather forecast and ii) to the operations due to the actual trajectory being somewhat different from the filed trajectory (actually a very small and not significant gain in this case). The totals are from the 121 rerouted flights for which all contrail data are available. The error bars represent the 95% confidence interval using a paired, nonparametric bootstrap over flights.

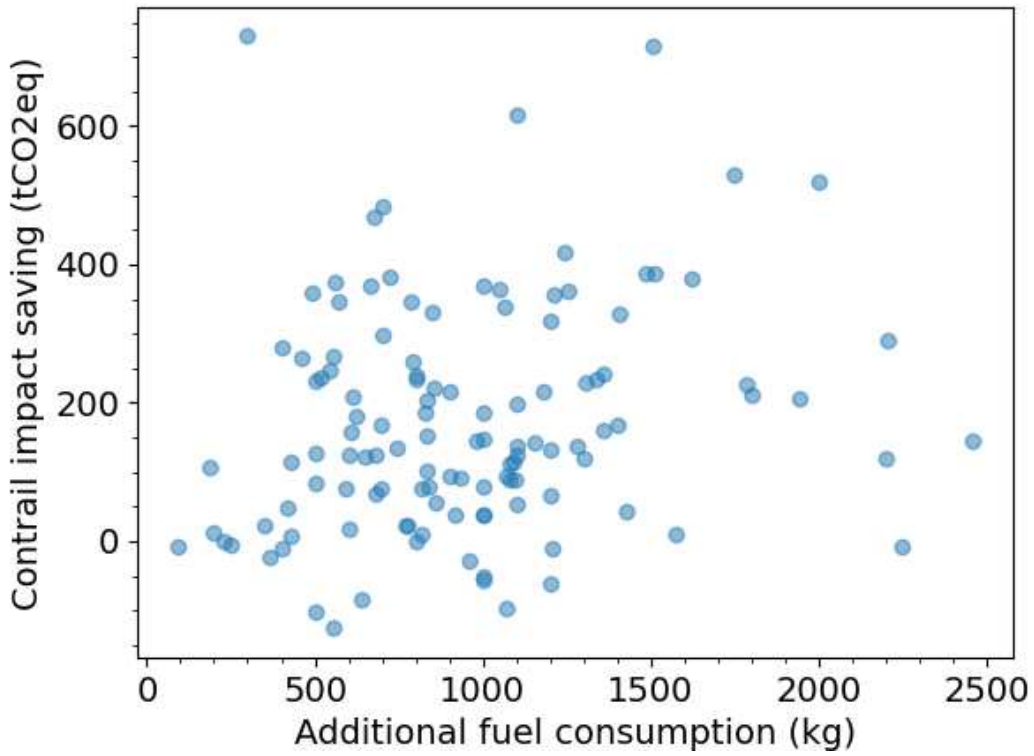


Figure 7. Contrail benefits (tCO_2e) versus additional fuel burn (kg). The contrail benefits are computed from the updated meteorology. The data are for the 130 rerouted flights.

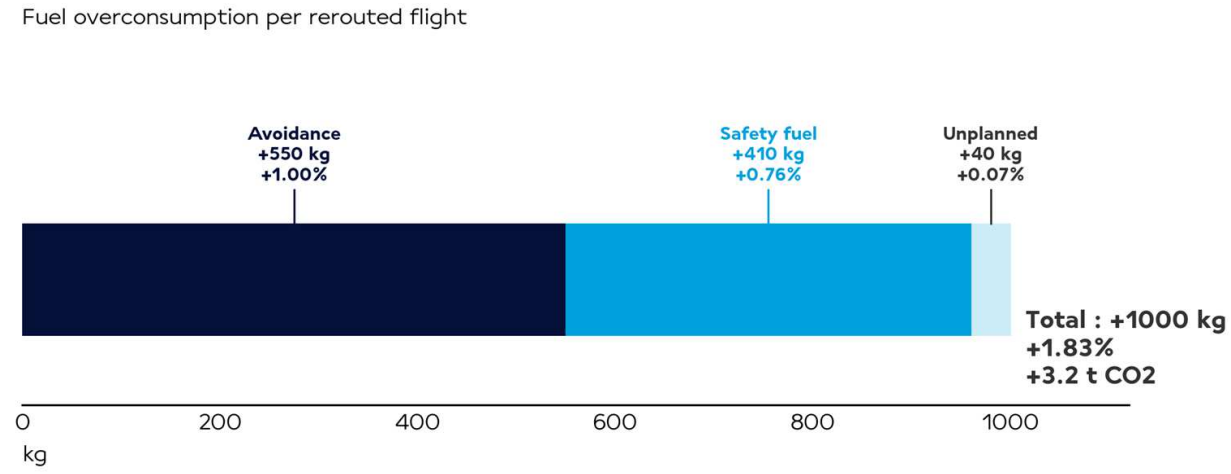


Figure 8. Breakdown of the fuel overconsumption (in kg and in % of the initial fuel burn estimate) due to contrail avoidance per rerouted flight as an average across 128 rerouted flights (two flights were excluded from the analysis because of changes in payload between the input and rerouted OFP).

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- data.zip
- AFSupplementary.pdf