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Towards climate compatible aviation: operational feasibility of contrail avoidance by flight path adjustments

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Abstract

Mitigating aviation's climate impact requires addressing both CO_2 and non-CO_2 effects. This study presents the operational feasibility from a real-world contrail-avoidance trial in the European airspace and demonstrates a pathway to reduce aviation's climate footprint. A simulated 70(±8)% reduction in contrail effect was obtained through vertical and lateral pre-tactical flight trajectory adjustments of 25 commercial TUIfly flights. The trajectory changes steered the flights around the airspace volumes that the Contrail Cirrus Prediction model CoCiP predicted to produce warming contrails. Our findings indicate that the trajectory adjustments to avoid formation of warming contrails increased fuel consumption by 2.8% and extended flight time by 1.7 minutes on average for real flights. Projecting the per flight average reduction to the 2019 global fleet indicates a potential 8-32% reduction in CO_2-equivalent emissions achieved via pre-tactical contrail avoidance. Our findings underscore the importance of integrating contrail avoidance into routine flight operations, and can contribute to a more climate neutral future for aviation.

Keywords: contrails, aviation, non-CO_2, climate mitigation

Introduction

Over the past few decades, research has increasingly revealed the substantial impact of non-CO_2 emissions from aviation on global warming, with estimates suggesting they account for one to two times more than the sector's entire CO_2 emissions since the historical start of aviation [1–5]. While aviation produces various non-CO_2 effects, contrail cirrus is identified as the largest non-CO_2 contributor to aviation's radiative forcing, although associated with large uncertainties [6–8]. The global mean contrail net radiative

forcing, estimated at 61–72 mW m^{-2} across studies that use 2018 [9] or 2019 [7] as the reference year, is in close agreement with satellite observations [10] and about 40% lower than the estimate of 111.4 mW m^{-2} by Lee et al. [5]. Global contrail radiative forcing is projected to grow with air traffic and could nearly triple to 160 mW m^{-2} by 2050 under high-growth scenarios [8, 11]. These findings and the fact that contrails alone may contribute more radiative forcing than an aircraft's CO_2 have led regulators [12–14] to develop a monitoring framework for non-CO_2 effects. A leading example is the European Union's non-CO_2 monitoring, reporting and verification system [15]. Further, there is a growing body of research investigating the uncertainties associated with contrails' climate impacts [16–19]. Recent risk assessments, that incorporate current uncertainties in aviation's non-CO_2 climate effects, favor prioritizing the mitigation of non-CO_2 impacts in trade-off scenarios [20, 21]. Together, this evidence highlights the importance of addressing non-CO_2 climate effects alongside CO_2 in the aviation industry's pathway to climate neutrality [22, 23].

Aircraft contrails induce high-altitude cirrus that exert radiative forcing through the reflection of solar radiation (cooling) and absorption of terrestrial radiation (warming), resulting in a net warming effect [5, 6, 24]. With no solar radiation at night, contrails only exhibit a warming effect. During day, both cooling and warming effects contribute to the contrail's radiative impact [25, 26]. All contrails form when the exhaust plume reaches liquid-supersaturated conditions described by the Schmidt-Appleman-Criterion (SAC) and they persist when ambient conditions are ice-supersaturated [25, 27], strongly influenced by the daily weather system. The majority of contrails sublimate quickly in ice-subsaturated air, those that persist can last for hours, spread and dominate the overall contrail climate effect [24, 28–30].

A small fraction of flights in humid, cold air creates persistent, warming contrails, and thus targeting contrail mitigation for just those flights could yield outsized climate benefits. One modeling study shows that roughly 1.5-3% of global flights are responsible for 80% of contrail warming [7]. A separate modeling study finds that just a few contrail-cirrus outbreaks generate the bulk of this contrail warming [31], although whether the flights that dominate warming coincide with those outbreak events remains unclear. While CO_2 emissions are relatively evenly distributed along the cruise phase, few flights and thereof only small fraction of their flight path contribute substantially to the overall net climate warming [7]. Mitigating contrail climate effect requires a multi-faceted approach including sustainable aviation fuels [9, 32, 33], next-generation engines that emit fewer particles [34], hydrogen combustion [35], and proactive air traffic management strategies [36, 37]. In addition to gradual improvements in fuel efficiency and the transition to sustainable aviation fuels [9, 33, 38], mitigating contrail climate effect by avoiding contrail formation can be achieved in the short term by adjusting flight routes. Small altitude changes of around 1-2 km, through climbing or descending, could potentially avoid the most climate-impacting contrails [39]. Model simulations show that for a subset of global flight traffic in 4 weeks the contrail climate effect could be theoretically reduced by 73% with 0.11% fleet-wide extra fuel consumption by adjusting flight trajectories [40], however, key effects of operational constraints and complexities are not included. Pre-tactical contrail avoidance typically involves making these trajectory adaptions during flight planning one day up to a few hours in advance, using weather forecasts to file alternative trajectories. In contrast, tactical avoidance involves real-time adjustments during flight [41], while strategic contrail avoidance focuses on broader strategies, such as restricting nighttime flights [42] or air traffic management airspace restrictions [43].

Here, we present first results from a real-world pre-tactical contrail-avoidance trial conducted in European airspace and evaluate the feasibility of mitigating aviation's contrail radiative forcing through proactive route planning. Specifically, we (i) use weather forecasts to identify flights likely to produce warming contrails, generate contrail-optimized avoidance trajectories for those flights, and execute the commercial flights; (ii) compare conventional cost-optimized, contrail-optimized flight plans, and real flown trajectories with reanalysis weather hindcasts to quantify changes in contrail energy forcing and

associated operational costs (fuel burn and flight time); and (iii) extrapolate these findings to global air traffic, demonstrating that modest rerouting of selected flights can substantially limit aviation's climate effect. The present work combines operational commercial contrail avoidance flights under European slot-based air-traffic constraints with a model-based assessment, while the evaluation with satellite imagery and impact assessment on air traffic control or other network effects is left for future work. Here, we focus on contrails, the primary climate effect that can be mitigated by flight trajectory adaption, and the associated CO_2 emission changes. We set aside other climate effects from NO_x or water vapor, which require to be targeted by strategic fleet adjustments rather than by individual flight changes, because their effects are broadly distributed and characterized by shallow gradients. Together, these results help to establish a pathway toward more sustainable aviation by showing that contrail mitigation can be operationally realized for selected scenarios under current European air-traffic constraints.

The contrail avoidance trial

The operational trial translates recent modeling advancements into an operational flight experiment under real European airspace conditions, where extreme traffic density and rigid slot-based controls make pre-tactical flight rerouting exceptionally challenging. A schematic illustration of contrail avoidance by flight path adjustments is shown in Figure 1. In practice, TUIfly GmbH applied pre-tactical measures by rerouting or adjusting the altitude of 25 selected flights to fly around regions forecast to form long-lived warming contrails. Figure 2a shows the flights rerouted for this study, including connections starting in Germany and heading towards both Canary and Greek islands in equal parts. Through its flight-planning tools, TUIfly in collaboration with Flightkeys [40] has incorporated contrail-prediction into daily operational planning. The tools are based on ECMWF IFS forecasts with the contrail cirrus prediction tool CoCiP [25] (details in Methods) which has been compared to in-situ measurements and remote sensing observations of contrail formation and contrail properties [38, 44–49] and is available via an internet application interface [50].

TUIfly's daily decision-making process began by reviewing the scheduled flight list, flagging those that are eligible for contrail-avoidance. For each flight that was predicted to produce warming contrails, flight plans were created with the FK5D software [40], which included one conventional cost-optimized flight plan and multiple contrail-optimized flight plans (details in Methods). Figure 3 illustrates the data-driven workflow for selecting contrail-avoidance flight trajectories. Vertical avoidance was the first choice, evaluated against turbulence, climb/descent segments required within cruise, flight level limits, and profile consistency. If vertical avoidance proved non-viable, lateral or combined avoidance options were considered. An avoidance flight plan was filed only when the additional fuel burn and time remained within TUIfly's pre-defined thresholds (excess fuel burn threshold: 2.5%; additional flight time threshold: 3 minutes); otherwise, the standard cost-optimized plan was retained.

For evaluation, three trajectories were considered per flight (planned cost-optimized, planned contrail-optimized, and real flown trajectory), see a vertical profile example in Figure 2b. The CoCiP model was run for each of these trajectories, using several weather states represented by the ECWMF ERA5 datasets (model levels, pressure levels and 10-member ensemble). We use ERA5 reanalysis data [51] as it provides a high-resolution, state-of-the-art characterization of the prevailing weather conditions during the flights. All ERA5 dataset runs were used to quantify the variability and uncertainty of the results from 25 flights. ERA5 humidity fields were corrected to better align with the observed IAGOS relative humidity over ice climatology through quantile mapping, as detailed in Wolf et al., 2025 [52]. Single flight predictions from CoCiP have demonstrated significant skill in predicting the contrail's radiative effect [53].

Here, we use both energy forcing [25] and the efficacy-weighted global warming potential (EGWP) [54] as primary metrics to characterize the contrail climate effect (details in Methods). Energy forcing

quantifies the integrated radiative impact of contrails over time and space by combining their optical properties, dimensions, and lifetime. To assess the climate impact, global warming potentials are calculated according to IPCC methodology [55], while the EGWP incorporates the mean efficacy of 0.37 as recommended for the non-CO_2 monitoring, reporting and verification system [56].

Results

Reduction of contrail and combined (CO_2+contrail) climate effect by flight path adjustments

Analysis of the flights reveals a mean energy forcing EF of 174(±13.4%) Terrajoule from contrails for cost-optimized flight plans and a substantial reduction when compared to both planned contrail-optimized and real flown trajectories, see Figure 4. We observe a significant 67% reduction (Mann-Whitney-U p-value 0.000036) in contrail energy forcing between cost-optimized planned and contrail-optimized planned trajectory. Also, a significant 70% reduction (same p-value) was observed between the cost-optimized planned and the real flown route. This incorporates the influence of operational reality – including air traffic control and environmental constraints to avoid certain airspace due to priority restrictions like turbulence, adverse weather, and the resulting delays – closely reflecting the reduction potential as shown by the difference of cost-optimized and contrail-optimized flight plan trajectory results. Although we expected operational constraints to limit the maximum achievable contrail energy forcing reduction, the data do not support this expectation. Across occupied European airspace, operational constraints had a limited, non-significant effect on the overall contrail EF reduction relative to planned trajectories (p-value 0.47). The consequences of these constraints are not yet fully understood and may include multiple effects, such as delays, which could either enhance or diminish the reduction. Hence, the reduction potential derived from the flight plans remains largely insensitive to operational constraints for the flights investigated in this study. The difference between pressure-level and model-level results in Figure 4 may arise from vertical smoothing of pressure-level data, which erases the fine-scale humidity and temperature structures retained in the native model level data, but this needs further validation. The coarser spatiotemporal resolution of the 10-member ensembles may contribute to some of the variations relative to pressure- and model-level data.

To assess contrail climate impacts on longer time scales, we apply the EGWP50 metric, the efficacy-weighted global warming potential over a 50-year horizon, which weights the contrail radiative forcing against the 50 years effect of the emitted CO_2 yielding the contrail-specific CO_2 equivalent ($CO_{2e,cont}$). The overall CO_2 equivalent (CO_{2e}) value then incorporates both the contrail component and the CO_2 emissions. Table 1 shows the net mean reduction of CO_{2e} in EGWP50. The uncertainty of CO_{2e} and $CO_{2e,cont}$ derived from global mean radiative forcing of contrails encompass weather variability, radiative transfer parametrization of CoCiP, cloud microphysics and feedback to natural clouds and water budget (full description of uncertainty treatment in Methods). The overall CO_{2e} reduction is 49(±22)%, indicating that contrail avoidance flights on average offset half of their combined climate impact in terms of CO_{2e} using the EGWP50 metric, including the CO_2 effect throughout the entire flight. The planned extra CO_2 emissions of 2.5% is comparable to that of the realized avoidance flights of 2.8% that were constrained by operations and is governed by the TUIfly excess fuel burn threshold. However, TUIfly's internal assessment, based on proprietary, fine-tuned aircraft-performance models, indicates an average additional fuel consumption that is lower than the values reported in this study. In addition, the contribution of operational constraints on rerouting to the additional emissions is uncertain, as conventional flights may be affected in a similar way. Consequently, further work is required to disentangle these effects. However, the combined CO_{2e} savings are largely driven by contrail reductions. Recent real-world trials show via satellite observations that tactical [41] and strategic [43] contrail avoidance can reduce contrail

formation, yet neither study quantified the resulting decrease in contrail climate effect. Our analysis fills this gap by estimating the reduction in contrail effect. The reductions reported in this study confirm that targeted pre-tactical contrail avoidance can be successfully realized through integration of current flight planning tools. Successful execution of contrail-optimized flight plans by TUIfly pilots underscores the importance of comprehensive pilot training for maximizing the benefits of contrail mitigation strategies.

Contrail climate effect reduction remains consistent across climate metrics

The chosen EGWP50 metric balances the climate impact of long-lived (CO_2) forcers and the incentive of a short-term reduction of short-lived (contrail-cirrus) non-CO_2 effects. However, a diverse set of climate metrics exists that pronounce the lifetime of radiative forcers and the consequent radiative imbalance differently, whether assessed at the surface or over the entire atmospheric column. To bridge the conceptual description of metrics with their practical implications, we present in Figure 5 the aggregated values for all 25 flights of various $CO_{2e,cont}$ savings based on different climate metrics for time horizons from 20 up to 1000 years. Flight fuel burn and associated extra emitted CO_2 is a commercially sensitive information, so the outcome of contrail avoidance is presented here as statistics over all flights, and equivalence metrics are normalized by the planned additional CO_2 emissions of the contrail-optimized trajectories. While the magnitude of estimated benefits varied substantially depending on the metric and the ratio of saved $CO_{2e,cont}$ to the planned additional CO_2 ranged from 6.8($\pm$3.0) to 450.4($\pm$202.7), the success criteria of achieving net climate benefit remained consistent across all assessed metrics. Our results are in agreement with simulations that demonstrate that the metric choice does not alter the rerouting decision [57]. Part of the current uncertainties regarding the climate impact of contrail-cirrus, particularly concerning the lack of independent global model verification [58] and the representation of cloud microphysics [59, 60], as well as the climate impact from embedded contrails [16–19] necessitate further research on the quantification of absolute contrail climate effect. In addition, current understanding of the dissipation of contrail induced energy imbalance within the atmosphere is rudimentary [61]. However, the choice of solely assessing climate impacts on surface temperature provides an incomplete picture and overlooks potentially crucial consequences for atmospheric dynamics and weather systems. Still, regardless of the climate metric employed, targeted contrail avoidance consistently demonstrated a net positive climate impact, reducing overall radiative forcing from flights. By the flight series, we have demonstrated the feasibility of contrail avoidance with a positive net climate effect.

Low global air traffic contrail avoidance cost estimates

To explore the broader impact of our findings, we next present a speculative extrapolation to the global fleet that provides an estimate of the reduction potential of contrail avoidance via flight routing. An estimated 18-24% of global flights in one year are projected to produce contrails [7]; these are either assessed as having a net cooling effect, thus precluding mitigation, or contribute only marginally to warming. The latter are not targeted for rerouting negating the need for fuel expenditure on avoidance. Here, we assume that 2-8% of all flights are subject to contrail avoidance rerouting representative for 80% of the overall contrail energy forcing. This assumption takes a cautious stance, given that simulations indicate fractions of only 1.5-3% [7]. Consequently, the vast majority (92-98%) of flights would remain unaffected. Monte Carlo simulations are used to account for uncertainty and to obtain statistically robust estimates for global air traffic changes in flight time, fuel burn, contrail energy forcing, $CO_{2e,\ cont}$ and CO_{2e} (details in Methods). Global air traffic extra fuel burn associated with contrail avoidance through trajectory adaptation are estimated at approximately 0.14% from our results (see Table 2). In addition, the mean increase in flight time of the analyzed 25 flights is 0.7% or 1.7 minutes determined by the difference of real flown and cost-optimized trajectories within this study. This additional flight time remains within

normal operational variability, resulting in very limited additional costs beyond the increase in fuel consumption. Based on our analysis of 25 flights within the high-density European airspace, we estimate that a 70% reduction in contrail effect is attainable for global operations. Consequently, the contrail avoidance strategy yields an estimated global air traffic reduction of 56% in $CO_{2e,cont}$ and 20% when expressed in terms of CO_{2e} using the EGWP50 metric (details in Methods). While our results are encouraging, related caveats warrant discussion. Our analysis is based on 25 mid-haul flights, which is a small sample size and limits application to global fleet. The flight selection is threshold-dependent and selective, and the size of the possible flights pool for fleet-wise avoidance remains unknown. In addition, contrail formation in high density airspace is nonlinear, with relatively few flights able to seed high-impact cirrus. Consequently, realizing the full benefit of contrail avoidance in such sectors requires rerouting the entire traffic stream, whereas in regions of sparser traffic density contrail avoidance for a single flight may suffice [62]. Therefore, effective air traffic management and operational-scale validation of contrail-optimized routing are required, because the effects on the air traffic network and air traffic control capacities are still poorly understood. Future research is essential to resolve the caveats outlined above and to validate the scalability of our findings. However, this approach to contrail mitigation demonstrates a cost-effective measure to reduce the contribution of contrails to non-CO_2 radiative forcing, offering a promising avenue for climate neutral aviation.

Conclusion

This study demonstrates that pre-tactical contrail avoidance through flight trajectory adaptation is a viable pathway to substantially mitigate the climate impact of aviation. In a real-world trial we rerouted 25 targeted TUIfly flights, achieving a mean reduction in contrail-energy forcing of 70($\pm$8)% as calculated with the CoCiP model. For this, we applied four different contrail-avoidance strategies: 60% of flights were routed below the contrail-formation zone, 12% above it, 12% laterally around it, and 16% along a combined vertical-lateral detour. The corresponding reductions in $CO_{2e,cont}$ range from 6.8 to 450.4 times the planned extra emitted CO_2 in different metrics with 20 to 1000 years time scales. Across all evaluation metrics, these reductions consistently yield a net positive climate impact. These results align with the findings of previous simulations [57]. The compromise metric EGWP50 used here results in 69.4($\pm$31.2) $CO_{2e,cont}$ savings in terms of planned extra emitted CO_2 for the avoidance flights. When extrapolated to the global fleet in 2019, the reduction in CO_{2e} is projected to be between 8% and 32%. Global air traffic costs are estimated at a range of 0.06% to 0.22% in additional fuel consumption. Hence, contrail avoidance represents a cost-effective mean of reducing aviation's non-CO_2 radiative forcing.

Our trial successfully demonstrates a reduction in contrail climate effect through vertical and lateral adjustments of flight trajectories, achieved with relatively low increases in fuel consumption and operational costs. The results show that contrail avoidance via pre-tactical flight planning is viable and that operational constraints can have a limited effect on the overall reduction. These findings highlight the potential for integrating contrail avoidance into routine flight operations as a cost-effective strategy for mitigating aviation's contribution to climate change. The demonstrated feasibility of integrating contrail avoidance into routine flight planning is promising, seconded by a recent risk assessment favoring non-CO_2 mitigation in trade-off situations [20]. Owing to the long atmospheric lifetime of CO_2, emission reductions cannot deliver an immediate climate benefit, as required for achieving the Paris Climate Agreement targets [63], whereas mitigation of contrail effects acts on much shorter timescales, although delays in implementation diminish the achievable benefits [64]. However, scaling up contrail avoidance operations will require advances in contrail research. Further validation beyond the model framework using real-world observational data is essential. While contrail-avoidance flights provide valuable proof-of-concept evidence, only coordinated large-scale flight trials can adequately assess the practical scalability

of contrail mitigation strategies. Such experiments should be conducted in close collaboration with air traffic management and control, because operational-scale validation that incorporates network effects is a critical next step toward climate compatible aviation. At the same time, continued model development remains critical. In particular, further evaluation is needed of simulated contrail geometry and advection, and, most importantly, of uncertainties in their instantaneous radiative forcing effects. Consequently, benchmark studies that incorporate comprehensive contrail observations are required.

Table 1: **Mean per flight statistics for CO_{2e}, CO_2, and $CO_{2e,cont}$ in tons for each trajectory type and associated changes.** CO_2 with 5% error in fuel consumption of underlying aircraft performance model on single flight basis [65] and $CO_{2e,cont}$ from contrails calculated using the climate metric EGWP50 and the standard deviation from the different weather states in parenthesis (details in Methods). Uncertainty of CO_{2e} and corresponding changes in parenthesis are derived with standard error propagation.

contributor	cost-optimized / t	contrail-optimized / t	real flown / t	potential / % (contrail-optimized - cost-optimized)	realized / % (real flown - cost-optimized)
CO_2	29.6(±1%)	30.4(±1%)	30.5(±1%)	2.5(±1.4)	2.8(±1.4)
$CO_{2e,cont}$	72.2(±44%)	23.8(±48%)	21.8(±52%)	-67(±30)	-70(±32)
CO_{2e}	101.8(±31%)	54.2(±21%)	52.3(±22%)	-47(±21)	-49(±22)

Table 2: **Global air traffic cost estimates for contrail avoidance.** Global air traffic extrapolation is based on the upper limit of 2%-8% for the fraction of optimized flights (representing 80% of contrail energy forcing, Teoh et al. [7]). The mean values and 5^{th} to 95^{th} percentile range of simulated distribution for additional fuel consumption, flight time increase, and contrail effect reduction per optimized flight are derived from the present study and extrapolated to represent real operational scenarios using a Monte-Carlo simulation (details in Methods). All values reflect global air traffic impacts, not airline-specific scenarios.

Parameter	per optimized flight / % (real flown - cost-optimized)	global air traffic / % Mean[5^{th}/95^{th}]
Flight time	0.7	0.035[0.016/0.054]
Fuel burn	2.8(±1.4)	0.14[0.06/0.22]
Energy forcing	-70 (±8)	-56[-45/-66]
$CO_{2e,cont}$	-70 (±32)	-56[-14/-98]
CO_{2e}	-49 (±22)	-20[-8/-32]



Fig. 1: **Concept of contrail avoidance via rerouting.** Concept of rerouting to fly above, around, or below regions predicted to form long-lived warming contrails.

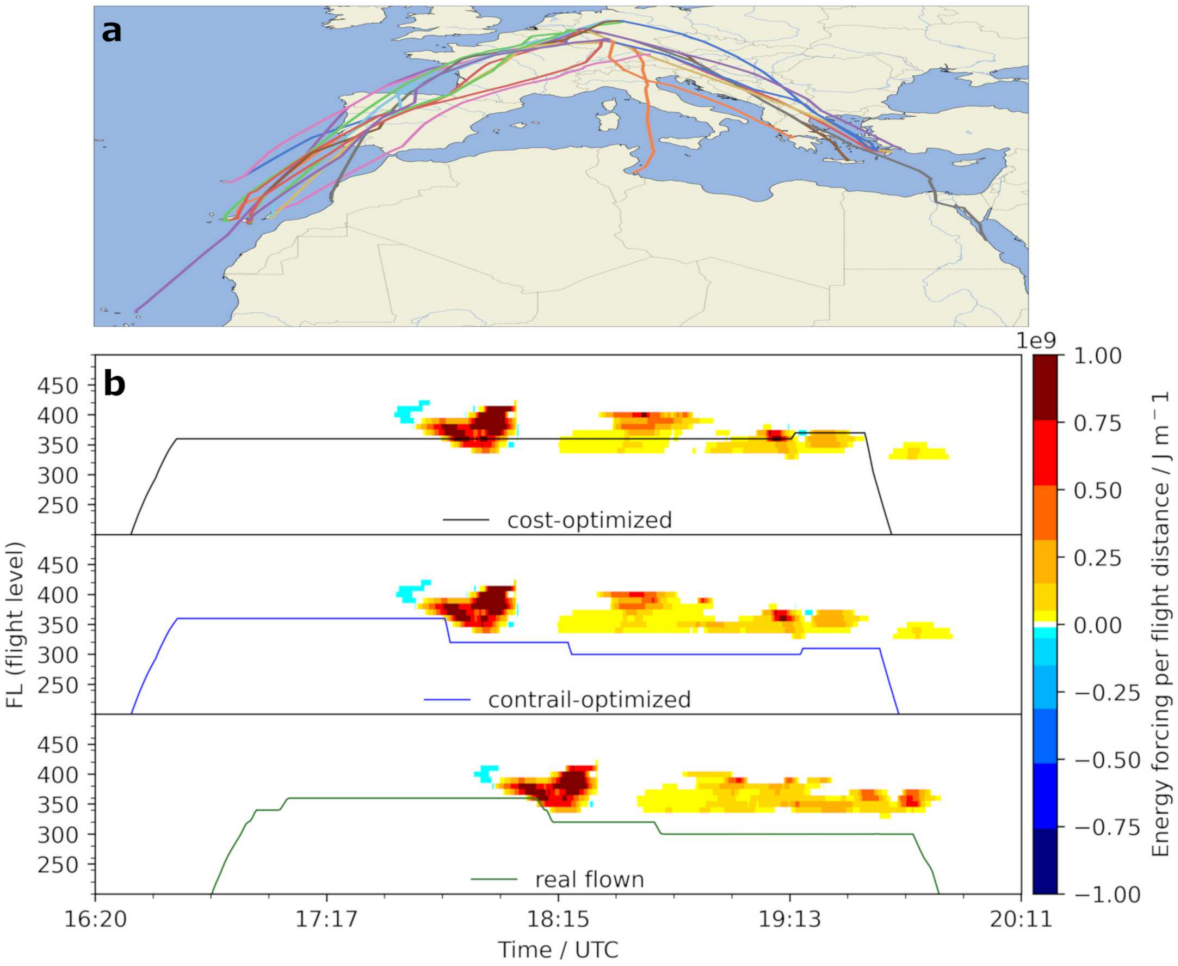


Fig. 2: **Flight paths of the contrail avoidance flights and vertical profiles of an example flight.** The 25 TUIfly flights originated in Germany and headed towards the Canary islands, Greece, or to African countries (a). (b) Vertical profiles of an example flight illustrate three scenarios: the cost-optimized trajectory (upper panel) passing through regions conducive to warming contrail formation, the contrail-optimized trajectory (middle panel) rerouted below the contrail-sensitive layer, and the real flown trajectory (lower panel) following the contrail-optimized flight plan with some delay. Contrail regions are calculated with the contrail model CoCiP in gridded mode.

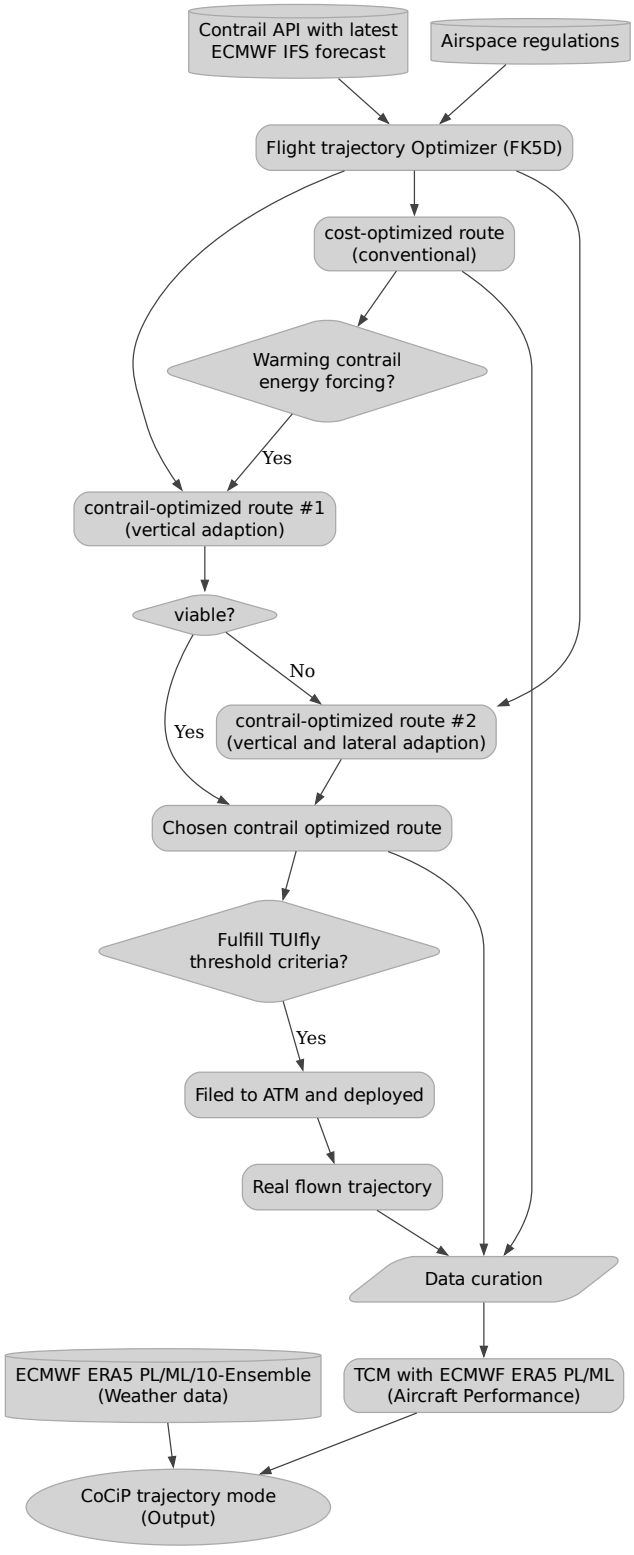


Fig. 3: **End-to-end workflow for selecting contrail-avoidance flight trajectories.** Meteorological inputs from the Contrail API based on an ECMWF IFS forecasts and air-space-regulation constraints are fed into the Flight-Trajectory Optimizer FK5D [40]. The optimizer generates a conventional cost-optimized baseline route and multiple contrail-optimized routes. Given the forecasted contrail-energy forcing, a vertically adapted contrail-optimized route is evaluated first. If that is not viable, a combined vertical-lateral adapted route is chosen. The selected contrail-optimized route is then checked against TUIfly's threshold criteria in fuel consumption or time. Routes that satisfy the threshold are filed to the air traffic management system, deployed, and executed, yielding the real flown trajectory, flown by the commercial TUIfly aircraft. Throughout the process, data curation and aircraft-performance modeling based on ECMWF ERA5 datasets are fed into CoCiP in trajectory mode to generate the output. The flowchart was created using the ANSI standard format.

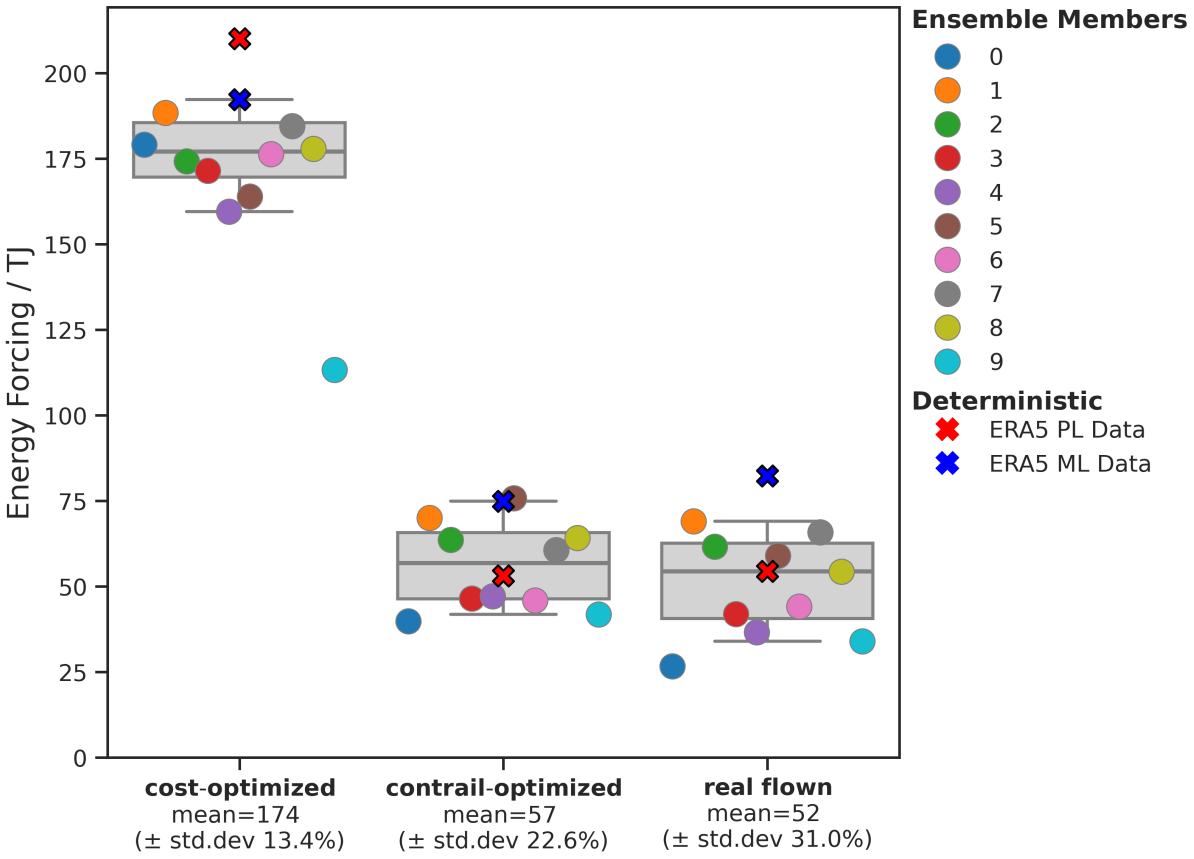


Fig. 4: **Mean energy forcing of the cost-optimized planned, contrail-optimized planned and real flown trajectory.** Mean energy forcings are derived from all 25 TUIfly contrail avoidance flights in different weather states of ERA5 ensemble members (colored points), pressure level (red cross) and model level (blue cross) data calculated with CoCiP in trajectory mode (details in Methods). The whiskers extend to the 5^{th} and 95^{th} percentiles, indicating the range that covers the central 90% of the data, while the box itself represents the interquartile range (25^{th} to 75^{th} percentiles) with the median shown as a line inside the box.

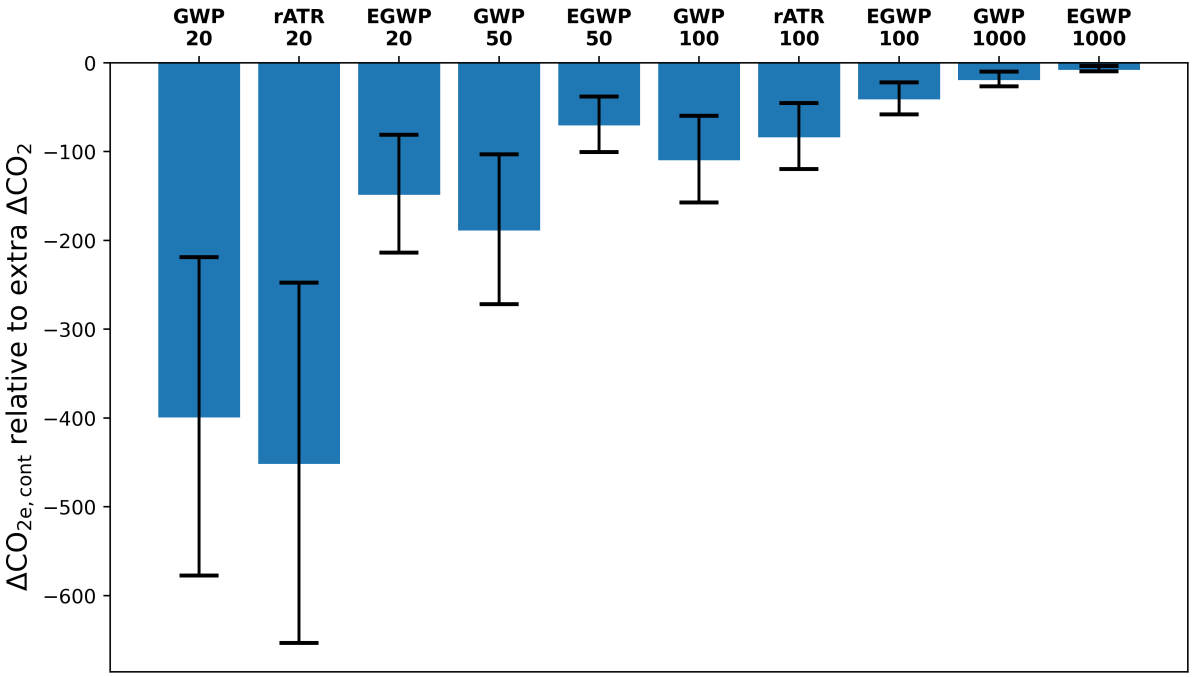


Fig. 5: **Aggregated $CO_{2e,cont}$ savings for all 25 avoidance flights relative to extra CO_2.** The savings are calculated using climate metrics Global Warming Potential (GWP), efficacy-weighted Global Warming Potential (EGWP), and relative Average Temperature Response (rATR) for time horizons 20, 50, 100, and 1000 years (details in Methods). All quantities are expressed as ratios relative to planned extra CO_2 emissions. Error bars include the standard deviation across the ERA5 10-member ensemble, pressure levels, and model levels, and uncertainties related to the radiative transfer scheme, cloud microphysics and feedback to natural clouds and water budget (details in Methods).

Methods

Contrail Cirrus Prediction Tool (CoCiP)

CoCiP is a physically-based Lagrangian plume model simulating contrail formation and evolution [25]. Driven by meteorological data, flight trajectory and aircraft parameters, CoCiP predicts contrail onset using the Schmidt-Appleman criterion [27] and tracks the contrail micro- and macrophysical properties over time, including ice crystal number concentration, size, optical depth, contrail geometry and radiative forcing. CoCiP operates in two modes: trajectory-based, simulating contrail evolution along defined flight paths [44, 48]; and gridded [66], calculating potential energy forcing per flight distance to identify regions of high persistent contrail formation and its warming intensity. The gridded mode utilizes a generic flight segment and assumes aircraft parameters, offering a broader assessment of the contrail formation potential. The gridded data is available via the contrail application interface, which serves as the data source for the FK5D flight planning software [40] which was used for the contrail avoidance flight plans in this trial utilizing the ECMWF IFS forecasts with lead times less than 24 hours to takeoff. Lead times less than 24 hours are stable enough to be used for pre-tactical contrail avoidance [67]. The contrail-optimized flight plans utilize a soft-constraint approach, weighting predicted contrail-warming airspace volumes as a cost factor within the optimization. For flight evaluation CoCiP was applied in trajectory mode with a 1-minute simulation time step and a maximum contrail age of 12 hours. Aircraft performance data were sourced from the Trajectory Calculation Module (TCM) [68, 69]. All other parameters for contrail simulation were maintained at the standard values within the open-source pycontrails library version v0.54.6 (Snapshot available at [70]). TUIfly employed B737-800W and B737-8MAX aircraft for avoidance flights; due to unmodeled volatile particle activation in the Leap engine (preventing accurate contrail simulation), emissions for both were mapped to the pycontrails emission model using B737-800s with CFM56-7B26/27 engines.

For evaluation, ERA5 datasets (model levels 67-90 (144-407 hPa): 0.25°×0.25°, Δt=1-hour; 37 pressure levels: 0.25°×0.25°, Δt=1-hour and 10-member ensemble: 0.5°×0.5°, Δt=3-hour) are used as meteorological data input of CoCiP. ERA5 has limitations in capturing humidity in the upper troposphere [71, 72]. Precise weather data, particularly relative humidity over ice, are crucial for quantifying contrail formation and potentially halve the contrail effect if not treated properly [26]. Therefore, humidity fields from ERA5 datasets were corrected using the *HistogramMatching* class provided within the pycontrails humidity scaling submodule. The method adjusts ERA5 humidity distribution to align with observed IAGOS relative humidity over ice climatology. It applies quantile mapping stratified by pressure level and latitude band [52]. The method supports pressure levels, model levels, and ensemble data—treating each ensemble member independently—ensuring consistent and realistic humidity correction for contrail modeling. In addition, cloud parameterization choices in ERA5 have been shown to lead to discrepancies in cloud phase and frequency [73], and cloud vertical distribution [74] relative to satellite retrievals, with potential implications for radiative effects of high clouds. Such biases originate from simplified microphysical assumptions and adjustments applied in the model, which can alter the vertical distribution and optical properties of simulated cloud fields compared to reality [75]. Despite its known limitations, we use ERA5 as a reference baseline in our analysis. All ERA5 dataset runs were used to quantify the weather variability and uncertainty of the results.

Trajectory Calculation Module (TCM)

Flight trajectories are modelled with the TCM providing realistic calculations of required flight performance parameters, such as thrust, fuel burn and engine efficiency [68, 69]. TCM applies a Total Energy Model (TEM) to describe changes of the aircraft state. The change of work by the forces acting on the aircraft (thrust T, drag D) equals the changes in potential and kinetic energy [76]:

$$(T - D) \cdot \mathbf{v}_{\mathrm{TAS}} = m \cdot g \cdot \frac{dh}{dt} + m \cdot \mathbf{v}_{\mathrm{TAS}} \cdot \frac{d\mathbf{v}_{\mathrm{TAS}}}{dt} \tag{1}$$

Cost-optimized and contrail-optimized planned trajectories of all 25 TUIfly contrail avoidance flights are modelled based on three-dimensional flight plan data assuming standard flight phases that represent common speed, climb, and descent practices per selected aircraft type. Based on the defined target conditions per flight phase, missing parameters can be determined applying the TEM. Lateral routing is based on waypoints from flight planning. Vertical changes to cruise flight level indicated in the flight plans are modelled with standard step climbs and descents [68]. Flight performance parameters for real flown trajectories are calculated from rearranging the TEM equation to required thrust, which can be calculated from observed changes in rate of climb/descent ($\frac{dh}{dt}$), speed $\mathbf{v}_{\mathrm{TAS}}$, acceleration $\frac{d\mathbf{v}_{\mathrm{TAS}}}{dt}$, and D. In both cases drag information is derived from aircraft specific aerodynamic fields and fuel burn is obtained from engine characteristics in dependence of thrust and operational conditions.

For this purpose, TCM comprises interfaces to different flight performance models. In this study, we apply Base of aircraft data (BADA) Version 4.2 flight performance data sets, that provide aerodynamic and engine characteristics as well as standard flight phase descriptions [76]. Meteorological conditions, namely temperature, pressure and wind, are derived from ECWMF ERA5 in both pressure and model level resolution. Flight track information is provided by TUIfly and complemented with additional data by FlightRadar24 for real flown trajectories.

Modelling uncertainties are primarily caused by inaccuracies in the flight performance models. BADA reports an average mean error in fuel consumption below 5% across the entire operational flight envelope for version 4 data sets [76]. Our analysis confirms these uncertainties in a comparable order of magnitude as long as the required aircraft-engine combination is available in the data base. In general, fuel burn and CO_2 are expected to be overestimated, however, relative consideration of results reduces uncertainties compared to analyses of absolute effects. Comparison with detailed manufacturer data shows a general suitability of BADA for environmental assessments, but restricts their applicability for optimization in economic studies [65]. While acknowledging the limitations of the BADA4 data, it was selected as comprehensive available dataset for aircraft performance characteristics.

Metric calculations

Global Warming Potential (GWP) was calculated by comparing the Absolute Global Warming Potential (AGWP) of contrails to that of CO_2 over a defined time horizon:

$$\begin{aligned} \mathrm{GWP}_{\mathrm{cont}}(H) &= \frac{\mathrm{AGWP}_{\mathrm{cont}}(H)}{\mathrm{AGWP}_{\mathrm{CO_2}}(H)} = \frac{\int_{t_0}^{t_0+H} \mathrm{RF}_{\mathrm{cont}}(t)\,dt}{\int_{t_0}^{t_0+H} \mathrm{RF}_{\mathrm{CO_2}}(t)\,dt} \\ &\approx \frac{\int_{t_0}^{t_0+H} i\mathrm{RF}_{\mathrm{cont}}(t) W(t) L(t) S_{\mathrm{Earth}}^{-1}\,dt}{\int_{t_0}^{t_0+H} \mathrm{RF}_{\mathrm{CO_2}}(t)\,dt} = \frac{\mathrm{EF}}{S_{\mathrm{Earth}} \mathrm{AGWP}_{\mathrm{CO_2}}(H)}, \end{aligned} \tag{2}$$

with $\mathrm{AGWP}_{\mathrm{CO_2}}$ mean estimates of 25.2/53.5/92.5 10^{-15}yr W m^{-2} $\mathrm{kg}_{\mathrm{CO_2}}^{-1}$ for 20/50/100 years from Joos et al. [77] which needs to be scaled with CO_2 emissions per flight

$$\mathrm{AGWP}_{\mathrm{CO_2,flight}}(H) = \mathrm{AGWP}_{\mathrm{CO_2}}(H) \cdot \mathrm{EI}_{\mathrm{CO_2}} \cdot m_{\mathrm{fuel}}, \tag{3}$$

and normalized to seconds with $\mathrm{sec}_{\mathrm{yr}}$=3.15576·10^7 seconds per year before calculating $\mathrm{GWP}_{\mathrm{cont}}$. Here, we use the CO_2 emission index $\mathrm{EI}_{\mathrm{CO_2}}$ 3.159 $\mathrm{kg}_{\mathrm{CO_2}}$ $\mathrm{kg}_{\mathrm{fuel}}^{-1}$, global mean radiative forcing of contrails $\mathrm{RF}_{\mathrm{cont}}$ and CO_2 $\mathrm{RF}_{\mathrm{CO_2}}$, instantaneous radiative forcing iRF, the native CoCiP output energy forcing EF, contrail width W and length L, and the surface of the Earth S_{Earth} with 5.10072·10^{14} m^2. The

efficacy-weighted Global Warming Potential (EGWP) was calculated as the GWP, scaled by an efficacy factor of e_{cont} 0.37 [56, 57], to reflect the lower radiative forcing efficiency of contrails relative to CO_2:

$$\mathrm{EGWP} = \frac{\int_{t_0}^{t_0+H} e_{cont} \mathrm{RF}_{cont}(t)\, dt}{\int_{t_0}^{t_0+H} \mathrm{RF}_{CO_2}(t)} = e_{cont} \cdot \mathrm{GWP}. \tag{4}$$

The Average Temperature Response (ATR) over a time horizon H represents the mean global temperature change resulting from a unit pulse emission of a radiative forcer. It is defined as the time average of the Absolute Global Temperature change Potential (AGTP), which gives the temperature response at a specific point in time. The relationship is given by:

$$\mathrm{ATR}_x(H) = \frac{1}{H}\int_0^H \mathrm{AGTP}_x(t)\, dt = \frac{1}{H}\int_0^H \left[\int_0^t \mathrm{RF}_x(s) \cdot \mathrm{IRF}_T(t-s)\, ds\right] dt, \tag{5}$$

where "x" represents the species in our case contrails and CO_2 and $\mathrm{IRF}_T(t-s)$ is the temperature impulse response function of the climate system. Here, we utilize the known AGTP_{CO_2} following Fuglestvedt et al. [78] Appendix 2 Equation (A3) for a unit pulse emission of CO_2 and use the IRF_T function of Boucher and Reddy [79] Appendix A for contrails with estimates of global mean RF_{cont} using:

$$\mathrm{RF}_{cont} = \frac{\mathrm{EF}}{S_{\mathrm{Earth}}\ \mathrm{sec}_{\mathrm{yr}}}. \tag{6}$$

Table 3: Absolute Global Temperature change Potential of CO_2 (AGTP_{CO_2}) and the temperature impulse reponse function of contrails ($\mathrm{IRF}_{T,cont}$) values used in this study for 20, 50 and 100 years time horizon.

	20 yr	50 yr	100 yr
AGTP_{CO_2} / K per $\mathrm{kg}_{\mathrm{fuel}}$	$7.734{\cdot}10^{-16}$	$10.057{\cdot}10^{-16}$	$10.277{\cdot}10^{-16}$
$\mathrm{IRF}_{T,cont}$ / ATR for RF in K per Wm^{-2}	0.0297	0.0136	0.007243

For completeness the respective values for the time horizons used in this work are in Table 3. For comparison the relative Average Temperature Response (rATR) is calculated similar to GWP with

$$\mathrm{rATR}(H) = \frac{\mathrm{ATR}_{cont}(H)}{\mathrm{ATR}_{CO_2}(H)} e_{cont}, \tag{7}$$

where ATR_{cont} scales directly with EF and ATR_{CO_2} with $\mathrm{kg}_{\mathrm{fuel}}$. In the same way as EGWP, the factor e_{cont} is applied to correct for the reduced radiative forcing efficiency of contrails.

Those GWP and rATR calculations have been compared for each flight to calculations that convert fuel consumption and CoCiP contrail energy forcing to GWP and rATR using normalized metrics calculated by the OSCAR intermediate-complexity climate model, as used in [57]. The second set of calculations agrees within 30% with the calculations in this paper. Differences are systematic and caused by the use of different climate response models, with different representations of climate feedbacks.

Fleet Extrapolation

We quantified the statistical uncertainty sourced from the respective mean per flight values in Table 2 of (i) the extrapolated total flight time and fuel burn changes, (ii) the global fleet-wide energy forcing, and (iii) CO_{2e} reduction using three independent Monte-Carlo chains with 10^5 iterations each.

For total flight time and fuel burn changes we drew a perturbed value for each iteration i from a normal Gaussian distribution with standard deviation $\sigma_X = X\epsilon$, where ϵ is the relative error. The flights subjected to rerouting are represented as an uniformly sampled share of the total from $[f_{\min} = 0.02, f_{\max} = 0.08]$. The extrapolated total was then $T^i = X^i/f^i$. The distribution $\{T^i\}$ yielded mean and $5^{\text{th}}/95^{\text{th}}$ percentiles.

For energy forcing the achieved mean reduction of 70% ($x_0 = -0.7$) was sampled from a symmetric standard normal Gaussian distribution u^i with $\sigma_x = 0.08$: $x^i = x_0 + \sigma_x u^i$. The reduction of EF is modeled under the assumption that the mitigation strategy affects 80% of the warming effect attributed to contrails. The global air traffic EF reduction R^i_{EF} was then obtained by linear transformation

$$R^i_{\text{EF}} = 1 - (0.2 + 0.8(1 - x^i)) = 0.8x^i. \tag{8}$$

From the $\{R^i_{\text{EF}}\}$ distribution we report mean and $5^{\text{th}}/95^{\text{th}}$ percentiles. The $\text{CO}_{2\text{e,cont}}$ is derived in the same manner as the energy forcing, employing $\sigma_x = 0.32$.

For $\text{CO}_{2\text{e}}$ reduction $R^i_{\text{CO}_{2\text{e}}}$ we draw randomly from $\{R^i_{\text{EF}}\}$ and $\{T^i_{\text{fuel}}\}$ of fuel burn changes

$$R^i_{\text{CO}_{2\text{e}}} = \frac{(\text{CO}^{\text{annual}}_{\text{2e,cont}}(1 + R^i_{\text{EF}}) + \text{CO}^{\text{annual}}_{2}(1 + T^i_{fuel})) - \text{CO}^{\text{annual}}_{\text{2e}}}{\text{CO}^{\text{annual}}_{\text{2e}}}, \tag{9}$$

where $\text{CO}^{\text{annual}}_2$ is the annual CO_2 emission of 885×10^9 kg, $\text{CO}^{\text{annual}}_{\text{2e,cont}}$ is the annual $\text{CO}_{2\text{e,cont}}$ emission based on annual EF of 999×10^{18} J and calculated with EGWP50 metric (Eq. 4). All reference values are drawn from the 2019 global data presented in Teoh et al [7]. The annual global air traffic $\text{CO}^{\text{annual}}_{\text{2e}}$ is the sum of $\text{CO}^{\text{annual}}_2$ and $\text{CO}^{\text{annual}}_{\text{2e,cont}}$. The distribution $\{R^i_{\text{CO}_{2\text{e}}}\}$ yielded mean and $5^{\text{th}}/95^{\text{th}}$ percentiles.

Treatment of uncertainties

Uncertainties for all quantities derived from global mean radiative forcing of contrails RF_{cont}, namely GWP, EGWP and rATR and the resulting $\text{CO}_{2\text{e,cont}}$ or $\text{CO}_{2\text{e}}$, are handled by applying the rough uncertainty estimates of RF_{cont} following Lee et al. [5] Appendix E with minor, explicit modifications. Below, we briefly state our assumptions and considerations for their use. When an assumption diverges from that of Lee et al. [5], the corresponding uncertainty is adjusted, while unchanged estimates retain the same uncertainty. Entries are omitted where not considered, primarily for aspects related to global climate model features that differ from the corresponding treatment in CoCiP:

A1 Adjusted uncertainty related to the radiative transfer scheme. Here, we use the reported relative uncertainties in short-wave (7%) and long-wave (11%) in CoCiP's radiative transfer parametrization [80]. We treat them as independent and assume a long-wave to short-wave ratio of 1.76 over Europe reported in Teoh et al. [7] yielding an uncertainty of 27% for the net RF_{cont}.

A4 Same uncertainty due to ice habit approximation of 20%.

B1 Adjusted uncertainty in RF_{cont} associated with the uncertainty in the upper-tropospheric ice supersaturation. We use the standard deviation from the different ERA5 datasets (pressure level, model level and 10-member ensemble) of about 11% for $\text{CO}_{2\text{e,cont}}$ and 17% $\text{CO}_{2\text{e}}$, see potential and realized reductions in Table1.

B2 Same uncertainty related to ice crystal number densities within young contrails of 20%.

B3 Same uncertainty in lifetime of contrail cirrus of 5%.

B5 Same uncertainty of the feedback to natural clouds and water budget of 15%.

We assume statistical independence of the uncertainties and want to note that the reported estimates of Lee et al. [5] pertain to global climate model estimates of RF_{cont}, while the assumed contribution of EF to RF_{cont} incorporated in the normalization in Equation 6 remains still poorly understood. In addition,

we do not attempt to infer an estimate for uncertainty of the efficacy. Hence, the overall uncertainty in $\mathrm{RF}_{\mathrm{cont}}$ and related quantities are roughly estimated to about 45% in this study.

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Declarations

Author contribution

C.V. and C.T. initiated the trial. C.V., D.P., S.K. defined and coordinated the trial. D.N., C.T. planned and coordinated the TUIfly flights and provided trajectory data. D.P. and S.K. organized data transfer. J.S. curated flight plan and trajectory data. Z.Z. performed aircraft performance calculations and sensitivity tests. D.P., M.J., K.W. and S.K. build data processing pipeline. J.M and S.K. perfomed data evaluation. S.K. performed the simulations and wrote the paper. C.V. J.M., Z.Z., Z.W., R.T., D.P. contributed to writing. N.B. assisted in metric data evaluation. All authors contributed and commented on the paper.

Competing interests

D.N and C.T. are employed by TUIfly GmbH. The other authors declare that they have no competing interests.

Data availability

The trajectory data is available at https://doi.org/10.5281/zenodo.18269821.

Code availability

The pycontrails repository that contains the CoCiP model is publicly available at https://doi.org/10.5281/zenodo.14714880 [70]. The grid-based CoCiP can also be accessed via an application programming interface (API) of Breakthrough Energy at https://api.contrails.org and https://nav.contrails.org.

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