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Operational Live-Trial for Contrail Prevention at the Maastricht Upper Area Control during 2021

Can persistent contrails be avoided in the real world?

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In memoriam John Green († 13 March 2022) [1]

***Abstract*—During the year 2021 the EUROCONTROL Maastricht Upper Area Control (MUAC) center, in partnership with the Deutsches Zentrum für Luft- und Raumfahrt (DLR), conducted an operational live trial to prevent contrails. Objective was to demonstrate that contrail prevention is operationally feasible and can be proven. The operational concept was to avoid ice super-saturated atmospheric regions and layers by deviating flights vertically, applying level clearances only. Deviations of 2000 feet in both directions were admitted minimizing additional fuel burn and hence additional CO_2 emission. The decision criterion used numerical weather predictions for ice supersaturation and persistent contrail. Observations from geo-stationary satellites and statistical analysis proved that contrails can be avoided. The experiment is the first operational trial of its kind where an entire airspace is used over a longer time. Based on the findings from the trial we investigate recommendations for future exploration.**

Keywords: Greenhouse Gases GHG, Non-CO₂, Effective Radiative Forcing ERF, Ice Super-Saturated Region ISSR, Contrail, Persistent Contrail

I. Introduction

[2] Condensation trails, or contrails, are ice clouds that form as a result of the mixing of cold, humid air with aircraft engine exhaust plumes. They affect the radiative balance of the earth by increasing global cloudiness, interacting both with incoming solar and outgoing thermal radiation. Contrails have been shown to result in net positive radiative forcing (RF), thereby contributing to climate change. Studies find that contrails and contrail cirrus may be the largest contributor to aviation-attributable RF, potentially exceeding contributions of aviation CO_2 emissions. This means that contrails associated with today's flight activity may result in as much instantaneous warming as the entire atmospheric stock of aviation-attributable CO_2 that has accumulated since the beginning of the jet age. Because reductions in contrail RF could be achieved quickly and could halve aviation-attributable warming, contrail avoidance strategies have been […] trialed at the Maastricht Upper Area Control (MUAC) center during the year 2021.

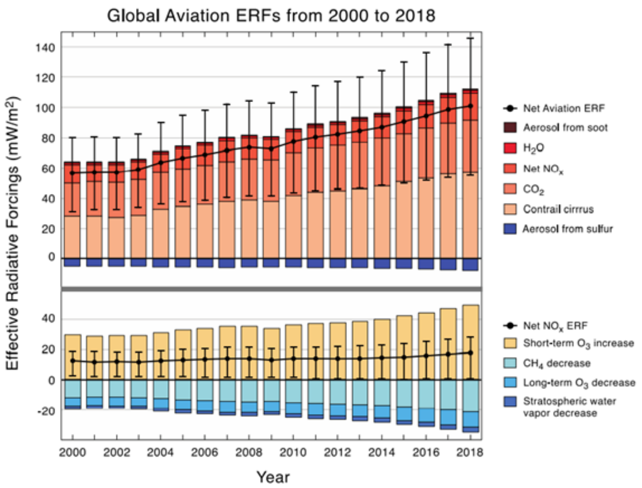

Figure 1 EASA [5] - Timeseries of calculated Effective Radiative Forcing (ERF) values and confidence intervals for annual aviation forcing terms from 2000 to 2018. The top panel shows all ERF terms and the bottom panel shows only the NO_x terms and net NO_x ERF. The reader should note that the high uncertainty mainly emanates from contrail and especially from contrail-induced cirrus, where models and researchers give different results.

Literature: Since the problematic of climate change is known and the contribution of non-CO_2 effects of aviation studied for a long time [3][4], there are summarizing reports on the topic; the most recent is probably the EASA Report [5], which covers non-CO_2 climate impacts of aviation, i.e. carbon dioxide CO_2, nitrogen oxides NO_x, ozone, methane, water vapor, aerosol interactions, contrail and contrail cirrus, see Figure 1. Mitigation of contrail and contrail cirrus by Air Traffic Management (ATM) have also been studied since a long time, e.g., reference [6][7][8]. There is no existing literature to the one presented here because this trial is the first of its kind.

Note: For completeness and convenience, and complementary to the already mentioned summarizing literature, an extended list of relevant publications can be found in the reference section of this research paper, covering significant publications for the meteorology and data sciences foundations ([18]-[58]).

Objective: Two research questions were formulated for the trial:

a) Is it possible for Air Traffic Control (ATC) to prevent contrails by tactical clearances with 2000 feet vertical deviations?
b) Can contrail preventions be statistically proven using geo-stationary satellite images, and applying object detection developed by the DLR?

II. DISCURSION ABOUT ALTERNATIVE OPERATIONAL CONCEPTS

At least three alternatives for operational contrail prevention by Air Traffic Management (ATM) can be envisaged:

TABLE I. PRE-TACTICAL FLIGHT PLANNING

Concept Pre-Tactical Flight Planning		
Pre-tactical flight planning can be done by re-routing the flight before filing its flight plan. Planned deviations can be lateral and vertical. Either airline operations have a powerful flight planning system with integrated ISSR/ERF routing functions, or are supported e.g., by the European Network Manager with centralized ISSR/ERF functions.		
	Pros	**Cons**
Globally plannable.	plus	
Environmental optimization possible, next to other criteria like timeliness etc.	plus	
Only equipped or participating airlines.		minus
Assumes high skill on the numerical weather prediction for ISSR and persistent contrail.		minus
Makes high margins and herewith inefficient trajectories, related to the skill of the weather prediction.		minus
ATC and AO need to be aware or be involved in collaborative decision making. Else the contrail prevention can have double negative impact.		minus

TABLE II. IN-FLIGHT INITIATED

Concept In-flight Initiated		
Pilots could use avionics to detect ISSR or use visual feedback. Flights could then report and request level changes. Systems could correlate with ERF related forecast available pre-flight.		
	Pros	**Cons**
Globally applicable.	plus	
Global and independent on ATC capabilities.	plus	
Very high precision at moment of prevention.	plus	
Only equipped or participating airlines.		minus
Needs feedback with other data sources to evaluate ERF impact.		minus
Environmental optimization not plannable or not possible anymore.		minus
ATC and AO need to be aware or be involved in collaborative decision making. Else the contrail prevention can have double negative impact.		minus

TABLE III. TACTICAL ATC DECISION

Concept Tactical ATC Decision		
Air Traffic Controllers (ATCO) deviate flights vertically based on numerical weather prediction or contrail detection systems. Decision point is as close as possible to real-time.		
	Pros	**Cons**
Moderate or high precision at moment of prevention, depending on available prediction and detection tools.	plus	
Applicable to high-density and -complexity airspace.	plus	
Applies to all airlines.	plus	
Local.		minus
Environmental optimization not plannable and only small-scale.		minus
In general, only vertical deviations possible.		minus

Even though just the third option of the tactical deviations concept was applied during the trial in 2021, this does not mean the other two options should be discarded; instead, we recommend that research be performed into the other two options and into combinations of the three options.

III. MUAC OPERATIONAL TRIAL CONDUCT

A. MUAC Airspace

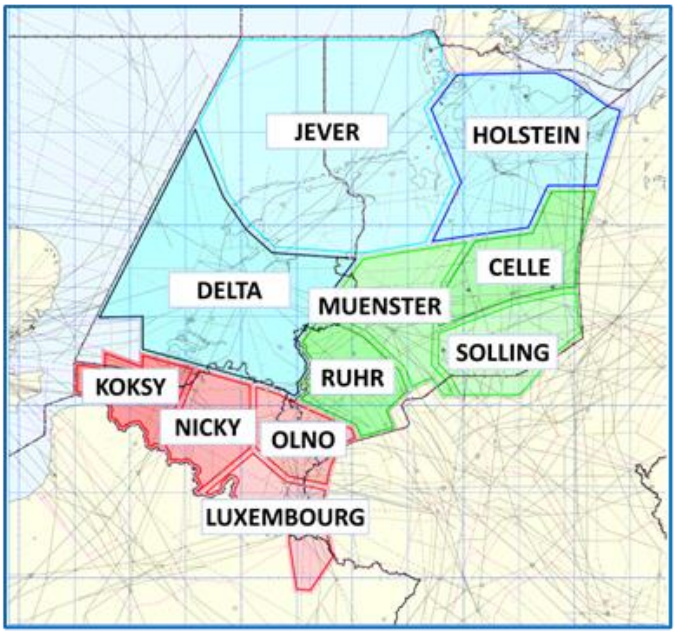

Figure 2-Area of responsibility for Maastricht UAC are Benelux and parts of Germany from flight level 245 and above.

The trial was executed across all MUAC airspace, i.e., Netherlands, Belgium, Luxembourg, north-west Germany, and the south-eastern part of the North Sea, between flight levels (FL) 245 to 660 corresponding to 384 to 53 hPa, or approx. 7.5 to 20 km above mean sea level for standard surface pressure, see Figure 2.

Over 17% of all European flights, i.e., flights in European airspace, are controlled by MUAC. It is a complex and dense airspace in the close vicinity of major airports, including Amsterdam, Brussel, Copenhagen, Düsseldorf, Frankfurt, London, Munich, and Paris.

B. Numerical Weather Prediction

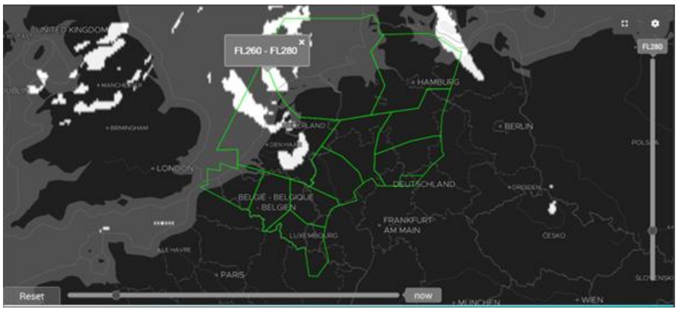

Figure 3 A sample picture from the Operational Support Data Retrieval (OSDR) tool, which is available to ATCO and operational planning staff. Areas with potential persistent contrails are shaded in white. The green lines indicate the borders of the MUAC sectors. Important for contrail prevention is to know the level and thickness of the contrail-prone areas.

MUAC receives the most recent aviation weather forecast from the German weather service (Deutscher Wetterdienst, DWD, ICON-Europe) every 6 hours at 04:00, 10:00, 16:00 and 22:00 UTC. Apart from the wind information this forecast also comprises temperature and relative humidity on pressure levels, which are then mapped to flight levels: FL 240 to 450, and pressures between 393 and 147 hPa.

The thermodynamic quantities are used to compute for each point in space and time whether contrails can be formed and whether a contrail, once formed, would persist. For the formation of a contrail the Schmitt-Appleman Criterion (SAC) [9] must be fulfilled. To allow practical rules for the controllers at MUAC, the SAC is determined for a "mean" aircraft.

With that, the remaining condition for contrail persistence is that the relative humidity with respect to ice, ri, must be at least 100%, i.e., the ambient air must be in a state of ice (super-) saturation.

Let:

ri	relative humidity w.r.t. ice
rw	relative humidity w.r.t. water
ew*(T)	water vapor saturation pressures w.r.t. liquid water
ei*(T)	water vapor saturation pressures w.r.t. ice

$$ri = rw\ ew^*(T) / ei^*(T) > 1 \qquad (1)$$

To compute ri, we need two water vapor saturation pressures: with respect to liquid water to ice. Since ri > rw ice saturation is possible at humidity below water saturation. Thus, the final condition is ri > 1.

Once the two conditions, the SAC and ri > 1, are fulfilled in an airmass, the formation of persistent contrails is possible from physical principles. In a later phase of the trial, the second condition was changed to ri > 0.98, a heuristically determined slightly lower threshold for ice saturation, in order to compensate a low humidity bias in the DWD forecasts as can be inferred by comparing with ERA5 and MOZAIC data [10].

With these conditions, a 4-D mask is determined for each time, longitude, latitude, and flight level. The default value for the mask is zero and then no persistent contrails possible. The mask takes the value of one if both conditions are fulfilled and then persistent contrails are possible. This mask was implemented in the MUAC OSDR (Operational Support Data Retrieval, Figure 3), which displays auxiliary information for the air traffic controllers.

C. Operational Planning for Trial Decision

The MUAC trial was scheduled from January 18, 2021, until October 22, 2021. All aircraft subject to cross contrail-prone areas during the night were targeted. Initially, the night started at 18:00 local time until the first morning shift starts at 06:00 local time. However, due to the cumbersome and highly manual decision process explained below, and the frequency of updates of the numerical weather prediction, only the first six hours of the night starting from the latest computation at 16:00 UTC were used.

For statistical reasons, the DLR requested to have a trial day every other day, which means that one of two days were skipped (even/odd calendar days), even if the conditions would allow for contrail prevention.

On those days where a trial would be plannable, a decision had to be taken which sectors should block which flight levels. During the experiment this process was highly manual:

1) Visual human interpretation of the European weather forecast from ECMWF, and a human decision on favorable weather conditions.
2) Comparison with the local OSDR tool providing the contrail-prone areas and their respective altitude information.
3) Editing the contrail-avoidance plan per flight sector per flight level per hour. A typical output of the consultation is in TABLE IV. , which shows the result of the consultation is an avoidance plan indicating which flight sectors should block level bands at times. This was communicated to the supervisors in the OPS room, which would then instruct the sector teams.
4) Communication of the avoidance table to the OPS room staff. The operations supervisors had to acknowledge the reception of the instructions.
5) Operations supervisors communicate verbally the information to the sector teams at MUAC, composed of two Air Traffic Controllers (ATCO) per sector also during nights. Late evenings have several sectors open depending on the traffic demand; early nights after 24:00 local time have three open sectors.
6) The ATCOs implement the blocked flight levels.
    a. Provide level clearance ‘for contrail avoidance climb/descent to flight level xxx’.
       Climbing or descending flights are unrestricted, i.e., they are excluded from contrail prevention.

b. Insert a Wx-info with a click of a button on the radar screen, which is also used for other weather-related event logging and ATCOs are accustomed to.

TABLE IV. AVOIDANCE PLAN

Sector	UTC Start	Until	Level Band
DEL	16:00	17:00	33-35
DEL	22:00	23:00	33-35
JEV	18:00	19:00	33-35
HOL	18:00	19:00	34-36
HOL	21:00	22:00	34-35
RHR	16:00	17:00	33-35
RHR	17:00	18:00	34-35
MNS	16:00	17:00	33-35
MNS	17:00	18:00	35-36

The logged Wx-events from the ATCO inputs, together with the trajectory information are extracted from the data warehouse and provided to the DLR, which is using it for its analysis of satellite images. The whole process is depicted in Figure 4. All elements of the process needed to undergo a critical safety analysis and acceptance from competent staff.

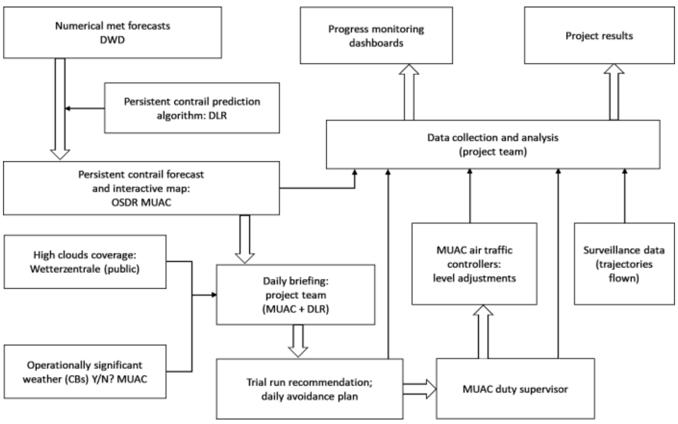

Figure 4 Highly manual process from consultation about worthiness of contrail prevention, to decision of contrail prevention, briefing the OPS room staff, execution of contrail prevention, and logging of information.

D. DLR Post Analysis with Satellites

The DLR conducted post analysis with satellite images.

Young contrails consist of many small ice crystals and possess mainly a characteristic linear shape. These properties are exploited for their detection in passive thermal satellite observations. Small particles induce larger brightness temperature differences in the atmospheric window between 8 and 12 µm. The linear shape can be used by image processing techniques to identify the presence of contrails. In this study we use the automatic contrail detection algorithm (CDA) initially developed by DLR for the AVHRR instrument aboard the polar orbiting NOAA satellites and adapted [11][12] to the spectral channels of the SEVIRI radiometer aboard the geostationary MeteoSat Second Generation satellites. Despite the worse spatial resolution compared to polar orbiting satellites, MSG/SEVIRI allows for observations every 15 min in the area under study such that the contrail prevention procedures can be evaluated in a timely manner. SEVIRI has a resolution of approx. 4.5 x 3.5 km^2 over Europe, while AVHRR has a resolution of 1.1x x1.1 km^2 at nadir. As a consequence, an AVHRR contrail has an estimated age of 20 min, while it takes longer – between ca. 1 h and 2 h for a contrail to fill a SEVIRI pixel. Thus, SEVIRI's observations are particularly well-suited for persistent contrails. 40 % of all contrails visually identifiable in SEVIRI data are also found by comparison with the automated algorithm on data from a whole-sky camera. Due to the moderate spatial resolution of SEVIRI it can happen, especially in regions with high air traffic density, that single SEVIRI contrails consist of more overlapping contrails or that other cloud structures, e.g., cloud edges or waves can appear line-shaped. Finally, one has also to consider that spreading or overlapping contrails can potentially lose their linear shape.

Using the CDA, the MUAC region was scanned for contrails, each of the eleven sectors separately for 18:00, 19:00, 20:00, and 21:00 UTC and for all 264 days of our trial. Deducting some individual missing data, the dataset consists of 11340 independent cases: 5544 and 5796 for even and odd days, respectively. We found persistent contrails on 2315 cases out of a total of 11340 cases. Figure 5 displays the brightness temperature differences from SEVIRI together with the detected persistent contrails on a selected day. Additionally, all flight tracks at and above FL 230 that occurred 60 to 90 min prior to the satellite image are also plotted, as these would be the flights potentially causing persistent contrails. Note that all flight tracks are plotted including those not passing a predicted area of potential persistent contrail formation.

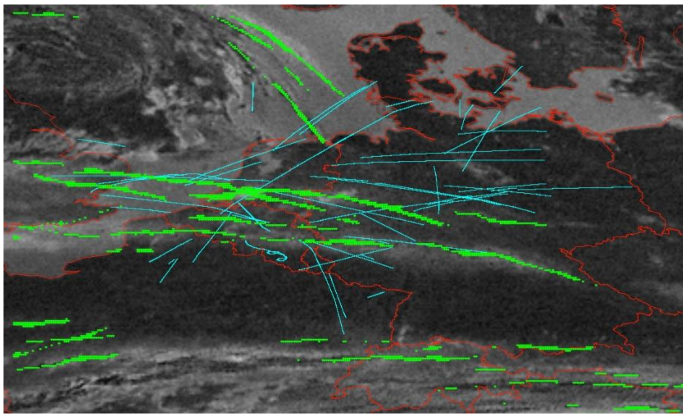

Figure 5 With Contrail Detection Algorithm (CDA) detected persistent contrails (green lines) on 26 April 2021, 21:00 UTC. Additionally, all flight tracks 60 to 90 min prior to the satellite image are also plotted (light blue lines).

E. DLR Statistical Analysis

The DLR conducted the analysis to verify the hypothesis that contrails can be avoided with statistical evidence, by categorizing the contrails from the satellite images into four groups, as illustrated in the TABLE V. . The categorization and counts were done manually, i.e., by visual interpretation of the output from the contrail detection algorithm,

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TABLE V. CONTINGENCY TABLE

		potential persistent contrails predicted	
		yes	no
persistent contrails observed	yes	***a*** correct	***b*** false negative
	no	***c*** false positive	***d*** correct

IV. OPERATIONAL RESULTS AND DISCUSSION

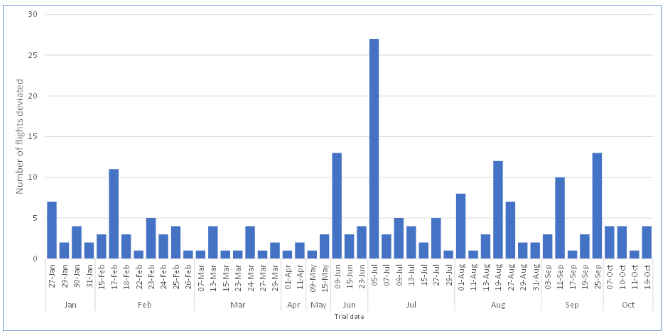

Figure 6 Counts of flights deviated daily during the trial.

Figure 6 gives the number of deviated flights during the trial that were logged. Over the course of the trial, ATCO indicated level changes to prevent contrails for 212 aircraft. Approximately 2.5% of flights in the area of responsibility were identified as crossing the areas indicated in the daily avoidance plans. Around 70% of these flights significantly changed altitudes inside MUAC sectors, climbing to their cruising levels or descending to destination aerodromes and herewith out of scope for the trial.

Many airlines contributed to the trial. No aircraft were missed. The MUAC project team had many bilateral meetings with airline operators (AO) to discuss the trial. The ecologic topic was well understood. Participation of airlines was very good and friendly, despite the difficult commercial situation during the COVID pandemic crisis.

Participation of ATCOs was good. Low training effort was deemed required with ATCO training consisting of a briefing sheet, and supervising staff who had been instructed prior to the trial. Overall discipline was good. The ecologic topic was well understood. ATCOs would have liked direct feedback about success of contrail prevention and would very much appreciate a climate-related performance indicator.

MUAC would like to have immediate feedback on the performance of contrail prevention for both, contrail prevention rates, and climate effect.

Due to the very low traffic counts no statement on airspace capacity could be given; and not enough ATCO were exposed to the procedure to collect representative feedback.

The counts of deviated flights are relatively low, considering the long duration of the trial. The reasons are:

a) The traffic demand was very low, so that not many aircraft crossed the contrail-prone areas, due to the generally low night traffic numbers, and especially the very low COVID traffic levels with high impact on the late afternoon passenger traffic; impact of COVID during the early night is neglectable, considering that most night traffic is cargo, which had normal flight counts during the pandemic.

b) The weather was particularly ‘bad’ during the year 2021, with many anti-cyclones crossing the MUAC area at high pace, and not giving long time windows to observe ISSR and persistent contrails. The night of July 5, 2021, with 27 flights as depicted in Figure 6 is not an outlier, but rather a ‘normal’ summer night at the level of usual expectation.

The highly human-centered process for contrail prevention that was invented for the experiment must be automated for future daily operations. The decision about blocked flight levels should be presented directly as an advisory on the radar screen, preferably on the flight label in form of a proposed clearance.

The analysis conducted by DLR was very labor intensive and took a long time, so that there was no feedback during the trial. This should be automated.

MUAC conducted some manual observations by comparing weather as seen from the window, together with the air situation picture, and the current display of contrail information on the OSDR. It became evident that the tool in its current form is not precise for both lateral and vertical information. To the excuse of the weather forecast service, it must be noted that the provided weather prediction was not made for this purpose.

The applied operational concept uses tactical clearances; the expected benefit being to have high precision on contrail prevention and herewith avoid unnecessary maneuvers or fuel burn. This can either be enabled by a highly improved numerical weather prediction, or now-cast information. As stated above, the skill of the used weather prediction was not sufficient. MUAC could imagine using immediate feedback from satellites in almost real-time: the first contrail is detected, the second is avoided. Numerical nowcasts could eventually be improved using direct information from the assimilation process, that could include other observations e.g., from avionics observations, LIDARs or ground-based cameras.

The interpretation of contrail-prone areas for persistent contrail were cumbersome. It is instructing to watch these areas and their evolution in a relatively small geographical area like MUAC in detail. Their small extensions and patchwork-like vertical occurrence make contrail prevention challenging. Filtering and masking of thick clouds was necessary and done.

Requesting pilot reports is possible and pilots do see other flights' contrails but have no view on the persistence of contrails. Pilot reports are not feasible at high ATCO workload. Pilot reports via airline operators are more likely feasible. Pilot observations during the night are possible depending on the moonlight.

Statements on the climate effect with measures of ERF were not objective of this trial.

Statements on fuel burn were not objective of this trial.

Statements on contrail cirrus were not objective of this trial.

Cross-verification of ISSR predictions using avionics sensors for improved measures of relative humidity were initiated during the trial but could not materialize in its time frame.

The trial only applied the operational concept for tactical contrail prevention; this does not invalidate the other concept elements for pre-tactical planning or in-flight deviations. A future architecture will most probably be driven by cost and other business opportunities, where it is to be hoped that an overall cost-efficient investment strategy can be found.

V. ANALYSIS RESULTS AND DISCUSSION

TABLE VI. RESULTS CONTINGENCY TABLE

		no action: potential persistent contrails predicted		aircraft deviated: potential persistent contrails predicted	
		yes	no	yes	no
persistent contrails observed	yes	13.01 % (442)	7.30 % (248)	0.19 % (5)	9.00 % (242)
	no	15.98 % (543)	63.71 % (2165)	0.67 % (18)	90.15 % (2425)

3398 and 2690 cases remain for even (no action) and odd (aircraft deviated) days, respectively, for the whole trial period. The resulting relative frequencies are displayed in the contingency tables. TABLE VI. Shows even (left, no action) and odd (right, aircraft deviated) days of the trial. The relative frequencies are in %. The tables are based on 3398 and 2690 cases for days with no action and with aircraft deviated, respectively. The numbers in brackets are the absolute frequencies (counts). Unfortunately, only 23 cases remain in the boxes ***a*** and ***c*** as, for instance, in many cases not all aircraft within one flight level and one sector could be deviated or the region of predicted potential persistent contrails was too thick (five flight levels or more).

The ratios ***c***:***a*** of the values in the left columns (potential persistent contrails predicted) are ~1.2 for the days with no action (no contrails avoided) and 3.6 for the days with aircraft deviated. This gives reason to assume that the trial was successful, i.e., that persistent contrails can be avoided by deviating air traffic. However, in the light of the small number of cases, where aircraft were deviated, statistical tests are necessary to analyze whether this outcome is statistically significant.

TABLE VII. CONDITIONAL RELATIVE FREQUENCIES

		no action	aircraft deviated
persistent contrails observed	yes	44.9 %	21.7 %
	no	55.1 %	78.3 %

(TABLE VII.) Conditional relative frequencies under the condition that potential persistent contrails were predicted [%]. The table is based on 985 and 23 independent cases for days with no action and with aircraft deviated, respectively.

We might perform a test whether the probability functions behind the contingency tables are statistically different. However, this test might be dominated by the relatively large values ***d*** with no potential persistent contrails predicted and no persistent contrails observed. Therefore, a different way is followed: To concentrate on the conditional relative frequencies under the condition that potential persistent contrails were predicted, calculated from the values ***a*** and ***c***.

We performed several statistical tests. All of these tests show at a significance level of at least 95% (up to 97.5%) that the outcome **a** (potential persistent contrails predicted and persistent contrails observed) has a significant higher probability, if no action is taken than for the case that the aircraft are deviated. The 95% confidence interval for difference between the two probabilities ranges from appr. 6% to 41%.

Hence, for real air traffic, persistent contrails can be avoided by Air Traffic Control; the statistical error of this statement is 5% or less.

VI. RESULT SUMMARY

The operational trial in the MUAC airspace took place from January to October 2021. Contrail-prone areas were predicted using numerical weather prediction and additional algorithms for persistent contrail formation. Operational contrail prevention was executed tactically at late afternoons and early nights by giving 2000 feet climb- or descent clearances, where climbing and descending aircraft were not considered. All eligible flights were deviated.

a) Is it possible for Air Traffic Control (ATC) to prevent contrails by tactical clearances with 2000 feet vertical deviations?

   Yes, the trial was the first of its nature by targeting a whole airspace of an air traffic control centre. Since the traffic levels were low during the trial period, no statements can be given for operational viability and airspace capacity, yet.

The supporting processes and tools need improvements, for all: automation levels, quality, quantity, feedback time, contrail- and climate reporting, etc. Most critical is a high-quality numerical weather prediction, or other enablers e.g., with contrail detection, etc.

b) Can contrail preventions be statistically proven using geo-stationary satellite images, and applying object detection developed by the DLR?

Yes, despite the very low count of deviated flights, the statistical analysis based on the contrail detection algorithm from satellite images could prove that persistent contrails can be avoided.

VII. Outlook

At the time of writing this paper, the contrail prevention trial is continuing at MUAC. MUAC conducts real-time ATCO simulations to evaluate the capacity impact and is working with additional partners or consortia to try to overcome the shortfalls, which were highlighted thanks to this first trial in 2021. DLR is actively participating or leading, many important and relevant action on national [13] and international level, e.g., [14]. As part of the consortia, the weather providers work on the forecast model [15]. There is hope that the contrail detection with satellites can be automated and improved, and there will be the 3rd generation MeteoSat providing better images soon for Europe. Scientific and industrial partners work on improved machine learning for satellite image analysis. Contrail prevention with prediction from machine learning is starting to be trialed in MUAC operations. Augmented ground-based cameras will be used for precise and quick verification, and the network of ground LIDARs to support the altitude detection of cirrus is planned.

In parallel, tools targeting the climate impact are progressing and will be incorporated into the decision chain, e.g., CoCiP [16] and the aCCF [17]. Heating and cooling effects of contrail and contrail-cirrus will then be elaborated.

And last not least, the whole industry on both sides of the Atlantic and beyond is picking up the subject, driven by the need to reduce the climate impact of aviation.

This trial is a small step towards climate-neutral aviation, but it marks a cornerstone from research to operations, and from the lab into the real world.

Acknowledgment

We are grateful to John Green's "Contrail Avoidance Group" for many inspiring discussions, which were one trigger for the present trial. We would like to acknowledge his life work.

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