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Can we successfully avoid persistent contrails by small altitude adjustments of flights in the real world?

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In memoriam John Green (†13 March 2022)

Abstract

This paper describes the first-ever operational contrail avoidance trial in the real world, which took place in the region of Maastricht Upper Area Control (including the northwest of Germany, the Benelux countries and part of the North Sea) in the year 2021. Contrail avoidance could be an efficient method for mitigating the climate impact of aviation. Applying a deliberate experiment design, air traffic was deviated every other day by changing the flight altitude by up to 2000 ft up or down if potential persistent contrails were predicted. Whether deviations were successful on average was checked using satellite images of high clouds and by application of a contrail detection algorithm, which makes use of the properties of contrails. Despite the fact that forecasting persistent contrails remains a challenge, the trial was successful at a significance level of 97.5 %, i.e., on average persistent contrails can be avoided for regular flights in the real world with a small intervention in the vertical flight path. The experiment is an important step towards a regular operational reduction of the aviation climate impact by means of air traffic management. Nevertheless, many open questions need to be solved prior to an operational implementation of contrail avoidance or climate optimised flight trajectories in legal ATM procedures.

Keywords: contrail avoidance, aviation climate impact, real flight trial, ice super-saturated regions, contrail detection

1 Introduction

Aviation influences climate change substantially stronger than would be expected from the amount of its CO_2 emissions. In contrast to many other anthropogenic activities, the non-CO_2 effects of aviation (beyond classical long-lived greenhouse gases) are relatively large, e.g., in relation to other major sectors of anthropogenic emissions. The aviation non-CO_2 effects comprise changes of the atmospheric concentrations of O_3, CH_4 and H_2O resulting from NO_x emissions, the formation of contrails and contrail cirrus, the direct emission of H_2O, the emission of aerosols and aerosol precursors with their direct radiative effects, and the indirect cloud effects resulting from aviation induced aerosols (e.g., Prather et al., 1999; Sausen et al., 2005; Lee et al., 2009; Lee et al., 2021). In terms of effective radiative forcing (ERF), the total of all aviation effects is about 3.5 % of the anthropogenic ERF, and the impact of the sum of the non-CO_2 effects is about 2 times as large as the CO_2-induced warming (Lee et al., 2021). This fraction of the non-CO_2 effects neglects the impact of the indirect aerosol effects, which have been estimated with extremely large uncertainty so far (Lee et al., 2021; see also Penner et al., 2009; Gettelman et al., 2013; Zhou and Penner, 2014; Penner et al., 2018; Righi et al., 2021).

In terms of both, radiative forcing (RF) and effective radiative forcing (ERF), the largest contribution arises from persistent contrails and contrail cirrus. From these, only a small fraction of these clouds with a particularly strong individual RF (so-called "big hits", see RAeS, 2019) contributes the largest share of the overall warming. Some authors estimate that only around 1–2 % of all flight distances flown lead to these big hits (e.g., Gierens, 2018; Teoh et al., 2020).

The non-CO_2 effects are short-lived, with CH_4 and related effects having the longest lifetimes, in the order of a decade. Therefore, contrary to CO_2, the impact of the non-CO_2 effects depends on the geographical position, altitude and time of the emissions, and on the actual weather situation at the time of emissions and the development of the weather after the emission. This opens a pathway to (partially) mitigate the aviation climate impact by flying preferably at locations where the forcing from the non-CO_2 effects is smaller than at neighbouring locations (see below for more details).

Reducing the climate impact by changing aircraft flight trajectories has been a topic of scientific studies for

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nearly three decades. E.g., Sausen et al. (1994, 1996) and Nodorp et al. (1996) studied the potential of reducing the NOx-related aviation-induced climate impact (in a simplified parameterization) by flying trajectories optimised for a minimal combined NOx and CO_2 impact. Hoffschild (1997) expanded the Sausen et al. (1996) method by including contrails. Other studies analysed the climate impact of globally changing flight altitudes, concentrating on contrails (e.g., Williams et al., 2002, 2003; Fichter et al., 2005; Filippone, 2010) or considering many of the aviation non-CO_2 effects (e.g., Frömming et al., 2012). In 2003, John Green (Green, 2003) wrote "*A strategy of contrail avoidance would be a powerful way of reducing the impact of air travel on climate. In, say, 20 years' time, improvements in air traffic management and meteorological information might well make such a strategy practicable.*"

More recent studies aimed at mitigating the aviation climate impact by optimising trajectories using so-called climate-change functions (CCFs, e.g. Grewe et al., 2014; Frömming et al., 2021) or algorithmic climate-change functions (aCCFs, e.g. van Manen and Grewe, 2019; Yamashita et al., 2021; Rao et al., 2022; Matthes et al., 2021). In particular, Matthes et al. (2020) found in numerical simulations that the aviation-induced climate impact can be reduced in the range of 50 % at the expense of 1 or 2 % additional operation costs. Analogously, Chen et al. (2014) and Sridhar et al. (2014) performed numerical studies in order to reduce the climate impact of aviation by alternative flight trajectories using the absolute temperature change potential as a metric. Baneshi et al. (2023) additionally included a conflict assessment into a method for climate optimal trajectories.

Other authors have concentrated on avoiding contrails for reducing the aviation-induced climate impact. Persistent contrails can only form if the atmosphere is sufficiently cold and humid (e.g., Schumann, 1996; Sausen et al., 1998). For triggering a contrail, the Schmidt-Appleman criterion (SAC) has to be fulfilled, and for contrail persistence, the formation has to occur in a region where the atmosphere is super-saturated with respect to ice (ice super-saturated region – ISSR), as will be explained in Section 2 of this paper (see also, e.g., Irvine et al., 2014). Hence, a simple recipe to avoid persistent contrails is to avoid flying through such ISSRs, where the SAC is fulfilled (Mannstein et al., 2005; see also Gierens et al., 2008). Such methods have been applied in several studies, e.g., Campbell et al. (2009), Sridhar et al. (2011), Chen et al. (2012), Evans et al. (2012), Wei et al. (2013), Ng et al. (2014), Amin and Alam (2015), Filippone (2015), Avila et al. (2019), Rosenow et al. (2016, 2018), Rosenow and Fricke (2019), Teoh et al. (2020).

Other "simple" possibilities are to fly more in the stratosphere, which is generally too dry for contrail persistence (Schumann, 2005); but such a strategy has adverse effects, caused by the longer residence times of emissions in the atmosphere leading to generally increasing impacts with altitude (e.g., Fichter et al., 2005). One might also think of flying at rather low altitudes, e.g. below 500 hPa; however, current jet aircraft are not designed for such low cruising altitudes. An interesting approach is to use sustainable aviation fuel in regions, where persistent contrails can form, which would result in contrails with smaller radiative forcing (Teoh et al., 2022).

Up to now, papers on mitigating the climate impact of aviation by means of air traffic management have been theoretical or numerical studies (including all the papers cited above). The present publication describes the first attempt to demonstrate that persistent contrails can be successfully avoided for commercial flights in the real world. We do not consider all aviation non-CO_2 effects nor the impact on climate change (incl. CO_2), we rather concentrate on persistent contrails as these can be observed from surface and space.

In the remainder of this paper, we present our concept for the demonstration of avoiding persistent contrails with real flights (Section 2) and describe our operational procedures (Section 3). In Section 4 we display the method and results of our contrails observations from satellite. The statistical evaluation of the contrail observations is the topic of Section 5. The paper ends with a discussion and conclusions (Sections 6 and 7, resp.).

2 Concept

Contrail formation is a thermodynamically controlled process. Although the emitted soot particles serve as condensation nuclei, contrails would form as well if no particles were emitted, as for instance for hydrogen powered aircraft. There is always sufficient aerosol in the ambient atmosphere to take over the role of condensation nuclei. Therefore, the so-called Schmidt-Appleman theory (Schmidt, 1941; Appleman, 1953; Schumann, 1996) that describes contrail formation, does not mention the presence of aerosol particles as a necessary condition; this is taken as granted and the theory is thus a pure application of thermodynamics. Contrails form if the Schmidt-Appleman criterion (SAC) is fulfilled, which states that the exhaust gas while expanding into and hence mixing with ambient air must transiently become super-saturated with respect to liquid water, such that tiny water droplets begin to form spontaneously. Whether this happens depends on temperature, humidity and pressure, but as well on aircraft and fuel characteristics, viz. the overall propulsion efficiency, the lower heating value of the fuel and the emission index of water vapour.

Even a casual observer notes that contrails can have a wide variety of lifetimes. On some days most contrails are short-lived (a few minutes), but occasionally contrails become quite old (up to several hours, they spread out over the sky and after a while, they look almost like natural cirrus clouds. These contrails are called contrail cirrus. It is the latter type of contrails that are relevant to the climate; the short-living ones that evaporate after a few minutes have a negligible climate impact. The long-living ones, i.e., those living approximately 30 minutes and longer, usually termed persistent contrails, are those that have a noticeable impact on climate. Operational contrail mitigation thus implies avoidance of persistent contrails. It is the relative humidity with respect to ice, r_i, that determines whether a contrail is short-living or persistent. Persistent contrails require a humidity high enough that ice crystals do not sublimate and this means r_i must exceed 100 %, or in other words, that the ambient air must be in a state of ice super-saturation (for a review of ice super-saturation and ISSRs see, e.g., Gierens et al., 2012). The latter state is quite frequent in the upper troposphere, such that aircraft fly on average between 10 and 15 % of their distances within ice super-saturated regions (Gierens et al., 1999). Aircraft trajectories have a mean pathlength of 150 km (with a very wide variability) within ISSRs (Gierens and Spichtinger, 2000). If the SAC is fulfilled in such an airmass, the aircraft produces a persistent contrail.

It is simpler to say "avoid flying through ISSRs" than to actually do it. There are several reasons why this has never been tried before. Deviating from the planned route increases flight time and fuel consumption, thus leading to higher operational costs. Blocking ISSR airspaces can lead to higher traffic in neighbouring sectors or adjacent flight levels, which may have safety issues and impact controller workload. Finally, the pilots have to react which increases their workload. However, ISSRs cover only a fraction of the flight paths, and thus flight times and fuel costs typically increase by fractions of a percent.

If we eventually want to be successful in minimising the aviation climate impact by avoiding contrails, in particular, those contrails with a large warming effect, we need to answer the following questions:

1. Can we predict the formation of contrails with a reasonable skill?

2. Can we predict the formation of persistent contrails with a skill that is sufficient for deviating air traffic?

3. Can we predict the RF associated with individual contrails with a skill that is sufficient for deviating air traffic?

The answer to question 1 is definitely "yes", as was shown in observational studies, e.g., Busen and Schumann (1995). Forecasting the occurrence of contrails has been a topic for military purposes for decades (e.g., Schmidt, 1941; Peters, 1993).

Forecasting persistent contrails is a difficult task with current numerical weather prediction models. Even re-analyses fail with respect to ISSRs (e.g., Gierens et al., 2020). In addition, measuring the effect of operational deviation has not been addressed before. Therefore, no answer has yet been provided to question 2. Rather it has been argued that it is premature to perform a trial that might give an answer to this question. Providing a positive answer to question 2 requires the ability to predict the occurrence of ice super-saturated regions and the ability to measure the effects of deviating air traffic. Shine and Lee (2021) argued that current predictions of humidity are not good enough to take the risk of burning additional fuel with an uncertain outcome with respect to avoiding persistent contrails.

Question 3 is the most relevant with respect to eventually mitigating aviation's climate impact by avoiding persistent contrails. Additionally, we would have to compare the climate impact due to reduced persistent contrails with the climate impact resulting from additional CO_2 emitted and from other non-CO_2 effects. However, a necessary condition for answering question 3 is a positive answer to question 2. Therefore, we postpone question 3 and in the present paper we rather show that the answer to question 2 is "yes".

In principle, executing a contrail avoidance trial for real flights requires three steps:

i) On the basis of a weather forecast, predict 3D regions where contrails form according to the SAC and where (simultaneously) humidity is saturated with respect to ice (i.e., the region is an ISSR). Do this at temporal resolution as high as the weather forecast allows. These regions are those with a potential persistent contrail, i.e., a persistent contrail would form if an aircraft entered the considered region.

ii) Vertically deviate the air traffic so that it does not enter the regions defined in step i).

iii) Evaluate whether deviating aircraft was successful, e.g., by analysing satellite images of contrails.

In the real world, the approach is more complicated. Neither the forecast nor the contrail detection is perfect. In addition, not every flight that should be deviated can be deviated while still adhering to all safety regulations and considering operational constraints. Additionally, contrail detection from satellite images is also not perfect (see Section 6 "Discussion"). With this premise, we can collect our data on predicted potential persistent contrails and observed persistent contrails and collect them in a contingency table as displayed in Fig. 1, e.g., as relative frequencies.

In order to learn whether deviating aircraft trajectories results in less contrails, we need contingency tables for cases with and without deviation of air traffic. Contrary to a lab experiment or a numerical study, in a real flight trial, we can only either deviate a flight or not. For each individual flight that is deviated, it is logically impossible to prove that something would have occurred if we had not deviated the flight. Therefore, we need a carefully designed statistical approach in order to separate the impact of deviating flights from the background variability.

Hence, we need both cases where flights are deviated and cases where they are not deviated. If the trial was successful, the contingency tables for both cases will be statistically significantly different. However, the ***b*** and ***d***

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

Figure 1: Illustration of the contingency table for predicting and observing persistent contrails.

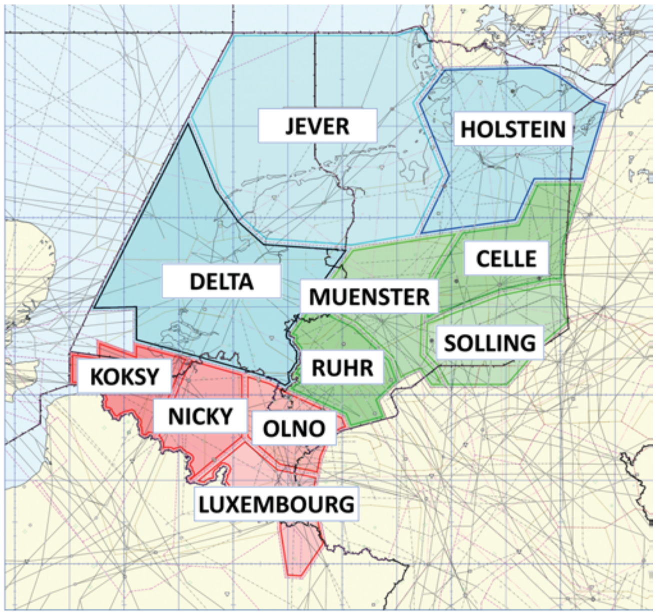

Figure 2: The area of responsibility of MUAC with its sectors over the Netherlands, Belgium, Luxembourg, the North-western part of Germany, and the South-eastern part of the North Sea. (Eurocontrol MUAC)

values should not be significantly different, as we would not take any action if no potential persistent contrail is predicted. Therefore, it is sufficient to only consider the elements ***a*** and ***c***, which are estimates of the conditional probabilities for observing or not observing persistent contrails under the condition that potential persistent contrails have been predicted.

In order to achieve a reliable result of our real trial, we need a concept that eventually allows a separation of the outcome of the cases with and without deviation of the air traffic, such that we eventually can fill the two contingency tables without bias. (i) We need clear and transparent rules, which allow an open outcome. In particular, a falsification of the hypothesis that persistent contrails can be avoided should be possible. (ii) A "desired" result should not determine the experimental design. (iii) A list of potential errors and weaknesses should be made.

In order to have cases with and without interference with the air traffic, only on odd calendar days we deviated air traffic according to the rules described in Section 3. On even days we did not interfere with the air traffic. This assures that we have approximately similar numbers of days with and without deviating air traffic. Additionally, this choice ensures that the weather situation has no impact on the general choice of whether we try to deviate the air traffic or not.

When evaluating whether we successfully forecasted persistent contrails, we sort our data with respect to clear rules as described in Section 5.

3 Implementation

An operational trial was prepared in the Maastricht Upper Area Control (MUAC) to prove the operational viability of avoidance of persistent contrails. Such a trial is only possible in close cooperation with an air traffic management (ATM) authority. EUROCONTROL MUAC has a decadal experience in developing and implementing new procedures for flight guidance (e.g., Ehrmanntraut, 2003; Ehrmanntraut and McMillan, 2007; Ehrmanntraut, 2010).

Our trial was executed across all MUAC airspace, i.e., Netherlands, Belgium, Luxembourg, north-west Germany, and the south-eastern part of the North Sea (Fig. 2), 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).

Over 17 % of all European flights, i.e., flights in European airspace, are controlled by MUAC (pre-COVID figures). It is a complex and dense airspace in the close vicinity of major airports, including Amsterdam, Berlin, Bruxelles/Brussel, København, Düsseldorf, Frankfurt, Hamburg, London and Paris.

MUAC receives regularly. i.e., at 04:00, 10:00, 16:00 and 22:00 UT, the most recent aviation weather forecasts from the German Weather Service (Deutscher Wetterdienst, DWD). Apart from the wind information this forecast also comprises temperature and relative humidity on a number of pressure levels, which are then mapped to flight levels (FL 240, 250, 260 etc. up to 450, covering pressures between approximately 393 and 147 hPa). The weather data are hourly provided on a regular $6.5 \times 6.5\,\mathrm{km}^2$ grid. Vertically, the resolution is 1000 ft (pressure altitudes, i.e. on flight levels).

The thermodynamic quantities are used to compute for each grid point in space and time of the DWD model ICON-Europe (Zängl et al., 2015) whether contrails can be formed and whether a contrail, once formed, would persist. For the formation of a contrail, the SAC must be fulfilled. In order to allow practical rules for

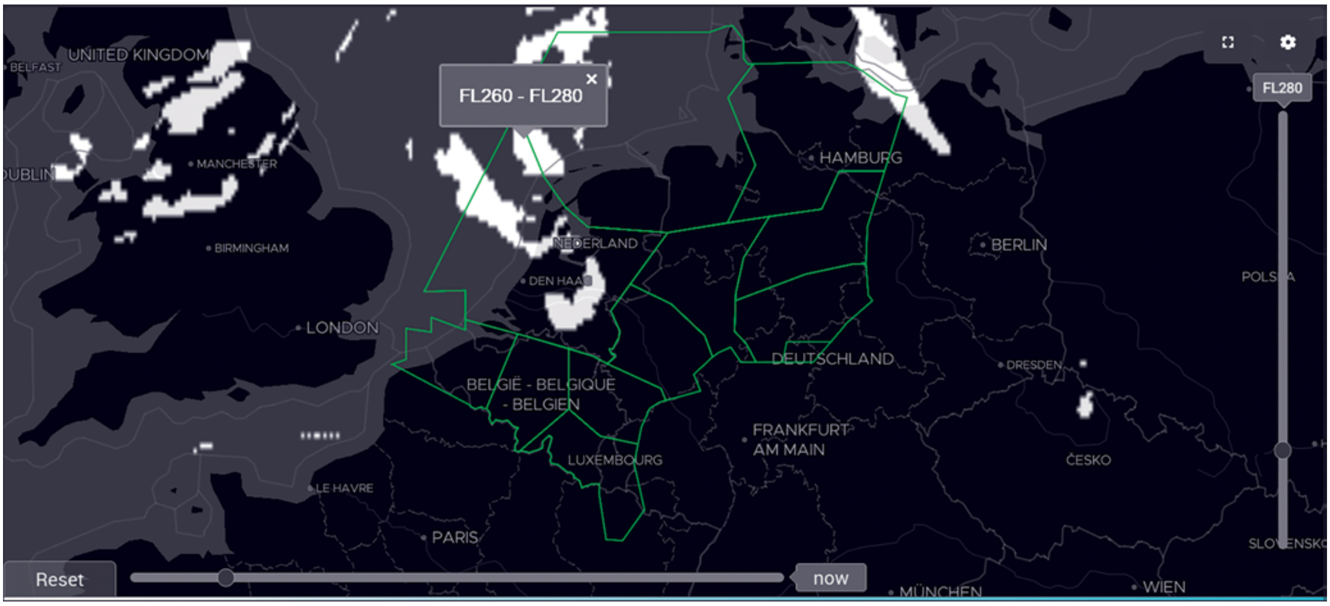

Figure 3: A sample picture from MUAC OSDR application. Areas with potential persistent contrails are shaded in white. The green lines indicate the borders of the MUAC sectors.

the controllers at MUAC, the SAC is determined for a "mean" aircraft. (See Appendix A1 for details).

With that, the remaining condition for contrail persistence is that the relative humidity with respect to ice, r_i, must be at least 100 %, i.e., the ambient air must be in a state of ice (super-)saturation. To compute r_i, we need two water vapour saturation pressures: with respect to liquid water, $e_w * (T)$, and with respect to ice, $e_i * (T)$. Note $r_i = r_w e_w * (T)/e_i * (T)$, where r_w and T are the relative humidity with respect to water and the temperature, respectively. Since $r_i > r_w$ ice saturation is possible at humidity below water saturation (see Appendix A1 and Gierens et al., 2012, for details). Thus, our final condition is $r_i > 1$.

Once the two conditions, the SAC and $r_i > 1$, are fulfilled in an airmass, the formation of persistent contrails is possible from physical principles. In a later phase of the trial (see below), the second condition was changed to $r_i > 0.98$, 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 (Gierens et al., 2022).

With these conditions, a 4-D mask is determined at every full hour between 16:00 and 22:00 UT, at each horizontal longitude-latitude grid point of the ICON-Europe model output and at each flight level between 240 and 450. The default value for the mask is zero (no persistent contrails possible). The mask takes the value of one if both conditions are fulfilled (persistent contrails possible). This mask was implemented in the MUAC OSDR (Operational Support Data Retrieval), which displays auxiliary information for the air traffic controllers (Fig. 3).

The trial using these calculations started on 1 Feb 2021, preceded by a preliminary test phase, in which the flights were not actually deviated. Starting from 1 July 2021 we reduced the relative humidity threshold to $r_i > 0.98$. The trial ended on 22 Oct 2021. The trial was mainly restricted to the hours between 16:00 and 22:00 UTC, to minimize the workload of the controllers.

On every odd day, members of the project team and MUAC supervisors met at 16:00 UTC. They analysed predictions sector by sector, identifying potential time periods, areas and levels where persistent contrails were likely to be formed, and constructed a daily action plan, indicating which levels should be avoided in each sector and at what time. The plan was a table with instructions for each sector with flight levels to avoid at specific times. These daily plans also fed the progress monitoring dashboards.

Contrail avoidance was not performed when the optical thickness of high clouds was too high to be able to analyse results using the satellite imagery, our chosen method of evaluation. The optical thickness of high clouds was estimated from representations of high cloud distributions from the DWD weather prediction model. Contrail avoidance was also not advised when the region of potential contrail formations covered more than 5 flight levels. Contrail avoidance was also skipped if there were significant CB clouds (thunderstorms) in the area, forcing aircraft to deviate from their planned routes to avoid adverse weather. Each decision was documented and logged.

With this procedure (for more details see Appendix A2) and with the reduced air traffic during the COVID-19 pandemic, a total of 212 aircraft (see also. Fig. A.2) were deviated vertically by 1000 ft or by 2000 ft, up or down, in order to avoid potential persistent contrails. This procedure ensured only a minimal impact on the trajectories of the aircraft. The low traffic levels due to the COVID-19 pandemic allowed the

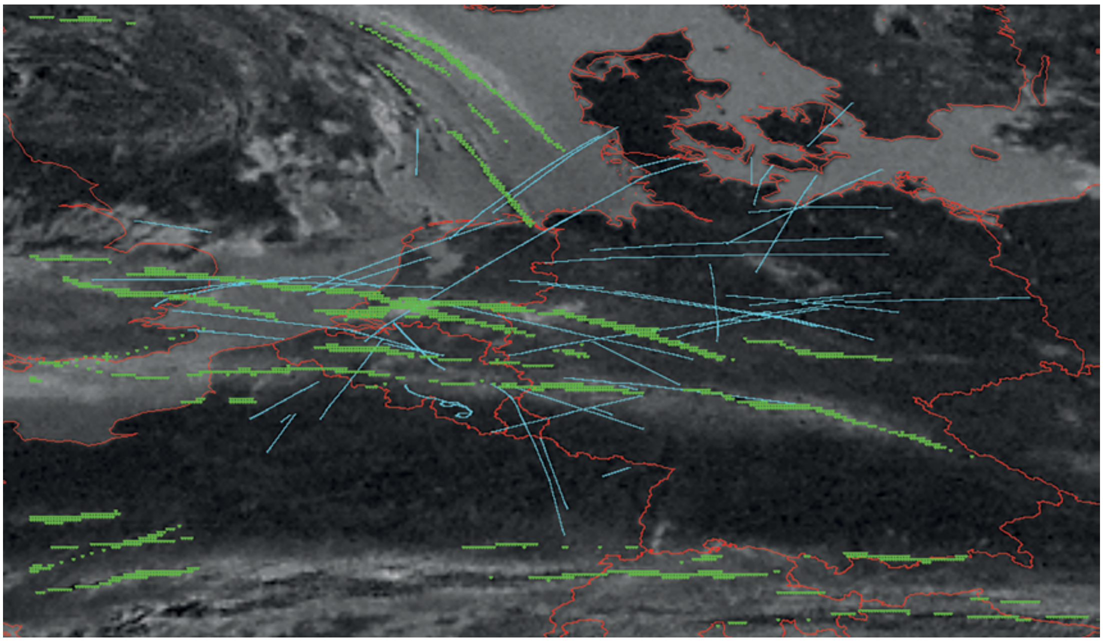

Figure 4: With CDA detected persistent contrails (green lines) over central Europe at 26 April 2021, 21:00 UTC. Additionally, all flight tracks 60 to 90 min prior to the satellite image are also plotted (light blue lines). The red lines indicate country borders.

performance of the trial without safety concerns for onloading neighbouring sectors.

4 Observations

In order to eventually evaluate whether our trial was successful in avoiding persistent contrails, we needed observations of such contrails formed over the MUAC area. This can be either done from the surface, if no low- or mid-level clouds exist, or from space, if no dense high-level clouds exist. The first method would require a continuous and area-wide observation by cameras with infrared sensors, which does not yet exist. However, from space we can make use of geostationary satellites, which provide rather frequent images.

Young contrails have a large number density of 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 (e.g., Ackerman et al., 1990). 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 Mannstein et al. (1999) for the AVHRR instrument aboard the polar orbiting NOAA satellites and applied in many studies (e.g., Meyer et al., 2002; Minnis et al., 2005; Palikonda et al., 2005; Meyer et al., 2007).

The CDA has been adapted (Mannstein et al., 2010) to the spectral channels of the SEVIRI radiometer aboard the geostationary Meteosat Second Generation satellites (Schmetz et al., 2002). 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. $4.5 \times 3.5\,km^2$ over Europe, while AVHRR has a resolution of $1.1 \times 1.1\,km^2$ at nadir. As a consequence, an AVHRR contrail has an estimated age of 20 min (Mannstein et al., 1999), while it takes longer – between ca. 1 h (Vázquez-Navarro et al., 2015; Duda et al., 2004) and 2 h (Gierens and Vázquez-Navarro, 2018) – for a contrail to fill a SEVIRI pixel. Thus, SEVIRI's observations are particularly well-suited for persistent contrails. Mannstein et al. (2010) demonstrated that 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 located at Oberpfaffenhofen (Germany). Furthermore, 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 and/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 whole 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. Fig. 4 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

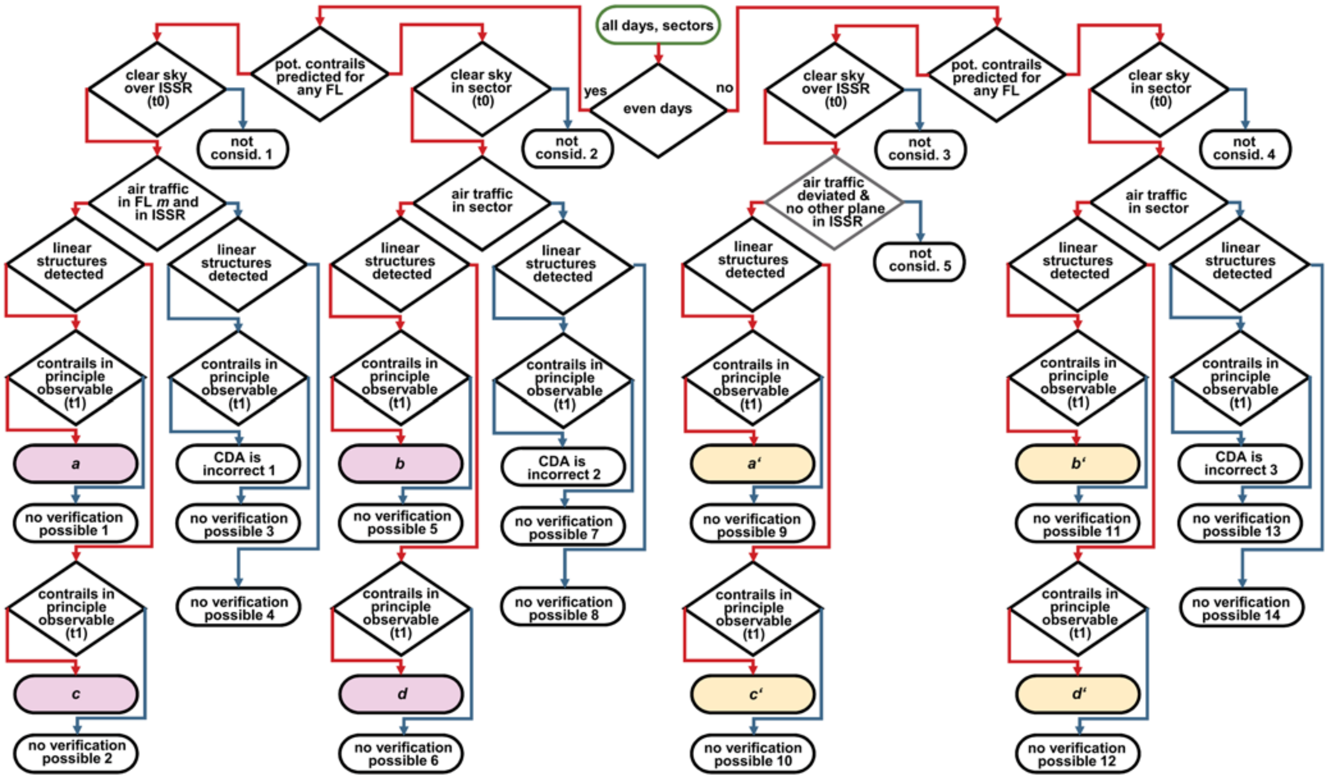

Figure 5: Overview of the classification algorithm for selecting the cases where an evaluation is possible. The output is collected in the oval, where the numbers refer to the rows in Table A.1 in Appendix A3. The pink and yellow ovals contain the input for the contingency table for days with (a' etc.) and without (a etc.) air traffic deviation. The red arrows lead to the input of the contingency tables. The blue arrows lead to the cases that are discarded.

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.

5 Evaluation

Many obstacles make it difficult to easily fill the contingency tables as mentioned in Section 2 for cases with and without deviating aircraft. We consider the 11 MUAC sectors (cf. Fig. 2), four time points per day (17:00, 18:00, 19:00, 20:00), and 264 days of trial. Discarding a few cases with missing data, 11340 cases must independently undergo a stringent classification process (Fig. 5) in order to eliminate all cases where an unobstructed observation was not possible. This process should not and does not depend on a “desired” result. The classification is carried out for all 11 MUAC sectors and at all times independently (see Appendix A3 for a detailed description).

The classification of the data starts with the decision of whether the day is even or odd (without and with potential action, resp., see Fig. 5). This is then followed by chains of further decisions (see Appendix A3 for a detailed description) that either eliminate cases or eventually fill the boxes ***a*** to ***d*** in the contingency tables (cf. Fig. 1):

- Are potential persistent contrails predicted for any flight level in the sector?
- Are there no high clouds in the sector (above the predicted potential persistent contrails if they are predicted)?

Below this decision the further decisions are different. In the case where *no* potential persistent contrails are predicted the chain continues:

- Is there air traffic in the sector?
- Are linear (contrail-like) structures detected?
- Are contrails observable (in principle)?

In the case where potential persistent contrails are predicted the questions are:

- Is there air traffic in the sector at a flight level for which potential persistent contrails were predicted, in the case of even days?
- Was traffic deviated and no other aircraft flew in the sector at a flight level for which potential persistent contrails are predicted, in the case of odd days?
- Are linear (contrail-like) structures detected?
- Are contrails observable (in principle)?

Table 1: Contingency table for 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).

		no action		**aircraft deviated**	
		potential persistent contrails predicted		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)

Eventually, 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 1). In the case of aircraft deviation, unfortunately, only 23 cases remain in the boxes ***a*** and ***c*** (see Fig. 1) 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). More details can be found in Appendix A3.

The ratios ***c*/*a*** (see Fig. 1) 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 analyse whether this outcome is statistically significant.

We might perform a test whether the probability functions behind the contingency tables (Table 1) are statistically different. However, this test might be dominated by the relatively large values ***d*** (no potential persistent contrails predicted and no persistent contrails observed). Therefore, a different way is followed: We concentrate on the conditional relative frequencies under the condition that potential persistent contrails were predicted (Table 2, calculated from the values ***a*** and ***c*** of Table 1).

We performed several statistical tests (see Appendix A4). 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 the difference between the two probabilities (i.e., the ***a*** values in the two contingency tables) ranges from appr. 6 % to 41 %.

Table 2: 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.

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

Hence, for real air traffic, persistent contrails can be avoided by air traffic management (ATM); the statistical error of this statement is 5 % or less.

6 Discussion

As stated above, for principle reasons, we cannot prove for any individual flight that vertically deviating by at most 2 flight levels can avoid persistent contrails, because we never know what would have happened if we had not performed the deviation. Therefore, we had to apply a statistical approach, which considers the ensemble of all flights.

The scientifically most difficult aspect of our trial is the evaluation, i.e. the check of whether deviating of aircraft tracks for contrail avoidance indeed has the desired effect on the average of all flights. The necessity and complexity of the evaluation flowchart show that a lot of assumptions have to be made which involve uncertainties. These comprise:

- Drifting of potential contrail formation regions over sector boundaries in the hour between prediction and evaluation can lead to errors in entries ***c*** and ***b*** in the contingency tables, in particular for small sectors.
- Contrails, which spread too slowly, may still be too narrow to be detectable in (today's) satellite images.

- The CDA may interpret cloud edges or coasts as contrails (false alarms). The additional analysis of cirrus clouds in satellite images tries to minimise such errors. False alarms in a sector with aircraft deviation can be misinterpreted as unsuccessful contrail avoidance. In contrast, the CDA might miss contrails because of, e.g., the high inhomogeneity of the background (Mannstein et al., 1999), thus enhancing the effect of the contrail avoidance or decreasing the number of detected contrails in no detection conditions.
- The forecast of ice super-saturated regions is not perfect for many reasons, in particular, because of the lack of enough high-quality in-situ humidity measurements for data assimilation at cruise altitude. Partly to compensate an underestimation of predicted ISSR frequency, the persistence threshold was lowered from 1.0 to 0.98 in the middle of the experiment. The latter causes additional uncertainty.
- Operational constraints and practice, in particular safety requirements, sometimes did not allow to circumvent contrail formation regions.
- Lower air traffic density during the COVID-19 pandemic made the additional work for the controllers easier to handle, but also resulted in a low number of cases to evaluate with high statistical confidence levels.
- The information on actually diverted flights is scattered between several independent data sources, the combination of which raises the potential for errors.

These problems can spoil the result, and their overall effect is hard (impossible) to quantify. Thus, for further contrail avoidance trials, it is important to note all details of every diversion manoeuvre, the callsign of the aircraft, date and exact time, the affected sector, the flight levels that were avoided and where it was switched to, and a complete account of the flight track. Such knowledge can later be used to calculate the expected position of the emissions which allows a much better control of whether contrail avoidance was really successful. This is, in particular, important if one wants to additionally compute how much additional fuel such manoeuvres cost and what the potential climate gain is.

It is also recommended to hold the weather briefings on all days and to produce similar tables with sectors and times where persistent contrails will form on days where no action is planned. This also helps in the evaluation.

7 Final remarks

In 2021 the first trial of avoiding contrails for real flights was performed for flights controlled by MUAC. Despite large challenges, we have been able to demonstrate that avoiding *persistent* contrails is possible on average. This is a necessary step towards eventually reducing the climate impact of aviation by means of air traffic control (eco-efficient trajectories).

It was beyond the scope of our trial to show that our trial on average resulted in a smaller aviation impact on climate. In particular, as our trial was partly performed during sunset we might have avoided cooling contrails.

The trial also uncovered shortcomings in the procedure: (1) More data on the humidity in the upper troposphere are required, which potentially would result in better humidity forecasts and, hence, better forecasts of potential persistent contrails. (2) Better satellite observations and better retrieval for detecting persistent contrails are necessary and should be supplemented by observations from ground cameras. (3) The process for deviating air traffic needs more support by numerical algorithms, potentially based on artificial intelligence.

While it is premature to establish general operational procedures for avoiding persistent contrails in the real world, it is necessary to better explore the pathway towards eco-efficient trajectories. Apart from working on the above-mentioned shortcomings, the demonstration of the possibilities to avoid persistent contrails needs to be further explored. In particular, the method should be applied to different regions and for situations with more dense air traffic than during the Covid-19 pandemic.

Eventually, we need to include all non-CO_2 climate impacts and the CO_2 emissions (i.e., fuel burn), weighted with a suitable metric, in the process of planning aircraft trajectories, such that the total climate impact of aviation is minimised. This will potentially impose further challenges for organising the (large-scale) air traffic in the light of the limited capacity of the sky.

Finally, note that it is not necessary that each individual flight needs to fly on a climate optimal trajectory. Remaining uncertainties will prohibit this and it is not absolutely necessary to reach this extremely stringent goal. It will be sufficient if the eco-efficient trajectories lead to a reduction of the climate impact on average, not each individual flight. (Procedures that are fault-tolerant should be aimed at.)

A1 Formation of persistent contrails

Contrails form, if the Schmidt-Appleman criterion (SAC) is fulfilled, which depends on temperature, humidity and pressure, but as well on the overall propulsion efficiency of the aircraft, the lower heating value of the fuel and the emission index of water vapour. In this paper, we assume that all aircraft use kerosene with a lower heating value (chemical energy) of 43 MJ/kg and with an emission index of water vapour of 1.25 (i.e., 1.25 kg of water is formed by burning one kg of kerosene). Furthermore, we assume that 40 % of the fuel's chemical energy is actually converted to kinetic energy of the aircraft (i.e., the overall propulsion efficiency is 0.4). With these assumptions fixed, the so-called contrail factor G (in Pa/K) is proportional to the ambient air pressure p:

$$G = \frac{p}{p_{\mathrm{ref}}} * G_0,$$

where $G_0 = 2\,\mathrm{Pa/K}$ when we choose for the reference pressure p_{ref} a value of 170.32 hPa.

With these assumptions, the maximum temperature that allows contrail formation is (following Schumann, 1996)

$$T_{\mathrm{max}} = 226.69\,\mathrm{K} + 9.43\,\mathrm{K}\ln(2p/p_{\mathrm{ref}} - 0.053) + 0.720\,\mathrm{K}[\ln(2p/p_{\mathrm{ref}} - 0.053)]^2,$$

where T_{max} is in K. T_{max} is typically around 233 K or −40 °C. The first condition for contrail formation is thus $T \leq T_{\mathrm{max}}$, and T_{max} depends only on pressure with our fixed assumptions. However, contrail formation at T_{max} would require that the ambient relative humidity with respect to water r_{w} is 100 %, which is not usual at common flight levels and which would mean that natural clouds would already exist, rendering contrail effects minor. This condition is relaxed at temperatures lower than T_{max}, where the ambient air must have a relative humidity with respect to water of at least $r_{\mathrm{w,min}}(T)$:

$$r_{\mathrm{w,min}}(T) = [e_{\mathrm{w}} * (T_{\mathrm{max}}) - G \cdot (T_{\mathrm{max}} - T)]/e * (T),$$

where $e_{\mathrm{w}} * (T)$ is the saturation vapour pressure (over liquid supercooled water) at a temperature T. Note that $r_{\mathrm{w,min}}$ becomes zero at sufficiently low T, which means that then contrails would be formed in dry air, just from the emitted vapour.

So, the SAC is fulfilled, and contrail formation is possible, if these two conditions are fulfilled:

$$T \leq T_{\mathrm{max}}$$

and

$$r_{\mathrm{w}} \geq r_{\mathrm{w,min}}$$

Contrails are persistent if

$$r_{\mathrm{i}} = r_{\mathrm{w}} e_{\mathrm{w}} * (T)/e_{\mathrm{i}} * (T) \geq r_{\mathrm{i,min}}$$

where we assumed $r_{\mathrm{i,min}} = 1$ until the end of June and $r_{\mathrm{i,min}} = 0.98$ from July on. r_{i} and $e_{\mathrm{i}}*$ are the relative humidity with respect to ice and the saturation vapour pressure over ice, respectively.

A2 Procedure to deviate aircraft for avoiding persistent contrails

During the daily contrail briefing, members of DLR, MUAC supervisors and the project team analysed SAC and ISSR predictions per sector thoroughly, identifying potential time periods, areas and levels where conditions for persistent contrails were likely to be present, and then advised to operations, which levels should be avoided. The briefing for contrail prevention took place at 16:00 UTC every other day, with a forecast for the following 6 hours. It had been decided to perform contrail prevention in the evening and night only as the impact on the environment of contrail cirrus is considered worse in the evening and night time as in the dark only the warming effect of contrails remains. The chosen time frame had the additional benefit of minimising the impact of the trial on MUAC operations and on the airlines. Avoidance was not performed when the optical thickness of high clouds was too thick to be able to analyse results using satellite imagery. For safety reasons it was also skipped if there were significant CB clouds in the area, forcing aircraft to deviate from their planned routes to avoid adverse weather. Each decision was documented and logged.

The daily avoidance plans were constructed using elementary air traffic control sectors as the building blocks. In some cases, especially in the northern part of MUAC area of responsibility, a single sector is big enough to be only partially covered by ISSR layers. (Note: in this section "ISSR" is used as a synonym for regions with potential persistent contrails.) In such a case, an avoidance decision was taken by the project team based on the proportions of the ISSR size relative to the sector size. The numbers of flights deviated and flights still crossing ISSR were based on the airspace selected in the avoidance plan, not the actual ISSR shapes and sizes.

The final decision go/no-go for each day of the trial was with the Executive Duty Supervisor. If the supervisor approved the trial to go ahead, they passed a table containing relevant information (sectors, times and level bands to be avoided) to the controllers. The supervisors ensured that safety of flights was never impaired by contrail prevention at any time (Fig. A.1).

The supervisor's decision-making was influenced by:

- The weather forecast, ongoing or expected weather events such as CBs or turbulence. Deviations in the horizontal and vertical plane are frequent during these circumstances and the resulting extra workload and requests for additional deviations need to be avoided.
- The traffic levels and complexity: capacity issues, as during periods of high traffic there is no spare time to provide additional instructions and eventual explanations as to the reason for the level changes. At the same time, traffic can be condensed in such a way that there is a need to occupy all available levels.
- High density military exercises due to the blockage of large parts of the airspace together with increased coordination workload.
- On-the-job training, though could be accepted if the coach agreed.
- Ongoing or planned system activities which mean increased workload at the sector level.

Air traffic controllers were instructed to keep aircraft out of predicted areas of ISSR by issuing climb or descend clearances by not more than 2000 feet (tactical air traffic control decision). Route deviations or level changes by more than 2000 feet to leave ISSR areas were out of scope of the trial. Aircraft with requested cruise altitude above or below levels of ISSR prediction could still be cleared through ISSR in climb or descend. Departing aircraft within MUAC area of respon-

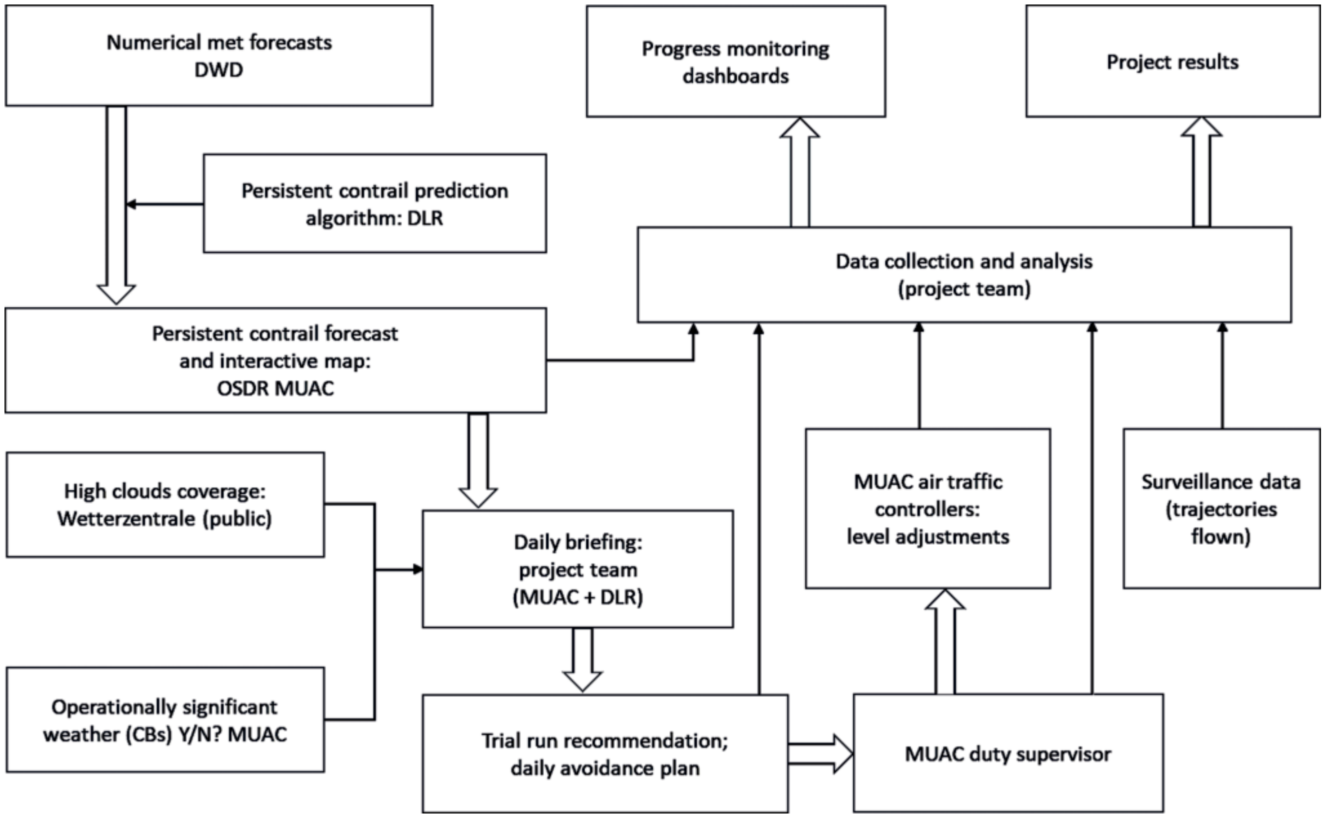

Figure A.1: Trial execution workflow.

sibility with requested cruise altitude in ISSR prediction could be kept below requested altitude on average for 10–15 minutes. Arriving aircraft could have been descended early.

Controllers were making special inputs in the system, to indicate that a given flight profile was adjusted because of the trial. It was not meant to be an accurate way to count it (some flights were initially tagged with the input, but finally not deviated), but it helped to monitor the efficiency of the avoidance execution, i.e., to check if controllers were able to still pursue the trial goals. Avoiding instructions were issued on a best-effort principle, and only if they did not interfere with the primary tasks of air traffic controllers.

The phraseology used for contrail prevention was "Due to contrail prevention climb/descend Flight Level XXX." Aircraft that have been deviated for contrail prevention reasons were marked with "WX". This input facilitated analysing the operations offline.

To monitor the project progress, and to assess the project impact on operations, MUAC collected the following data for further analysis: surveillance data – flown trajectories (ASTERIX format plus XML preprocessed data), numerical weather predictions of the areas where the persistent contrails are expected, together with their corresponding input data (netCDF), daily yes/no decisions and daily avoidance plans from the project team (originally in Microsoft Excel, automatically imported to Oracle database and Tableau), the list of flights marked by air traffic controllers as deviated for contrail prediction (CSV displayed in Tableau), and some qualitative feedback from air traffic controllers and supervisors (surveys). Some of this data was daily visualised in a form of dashboards, to let the project team monitor the execution of the plan, and to be able to respond to anomalies (Fig. 3). The data was shared with DLR for the purpose of validation of the trial outcome.

Over the course of the trial, controllers indicated level changes to prevent contrails for 212 aircraft (see also Fig. A.2). During the trial, contrail prevention was only achieved by adjusting vertical profiles and by no more than 2000 ft. Crossing the avoided region in climb or descent is unrestricted. During the trial hours, 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 – out of scope for the trial.

MUAC did not estimate the impact of specific tactical manoeuvre on a fuel consumption case by case. Generally, the expected impact of a temporary deviation of 2000 feet at a cruising altitude is relatively low, but the accurate calculation would require additional details about every specific flight. Some factors to consider are listed below. Filed levels from the flight plans do not always perfectly match with flown optimum altitudes. If the flight is planned and conducted below its optimum altitude (for example because of the independent ATC constraints) – a descent of 2000 feet will typically

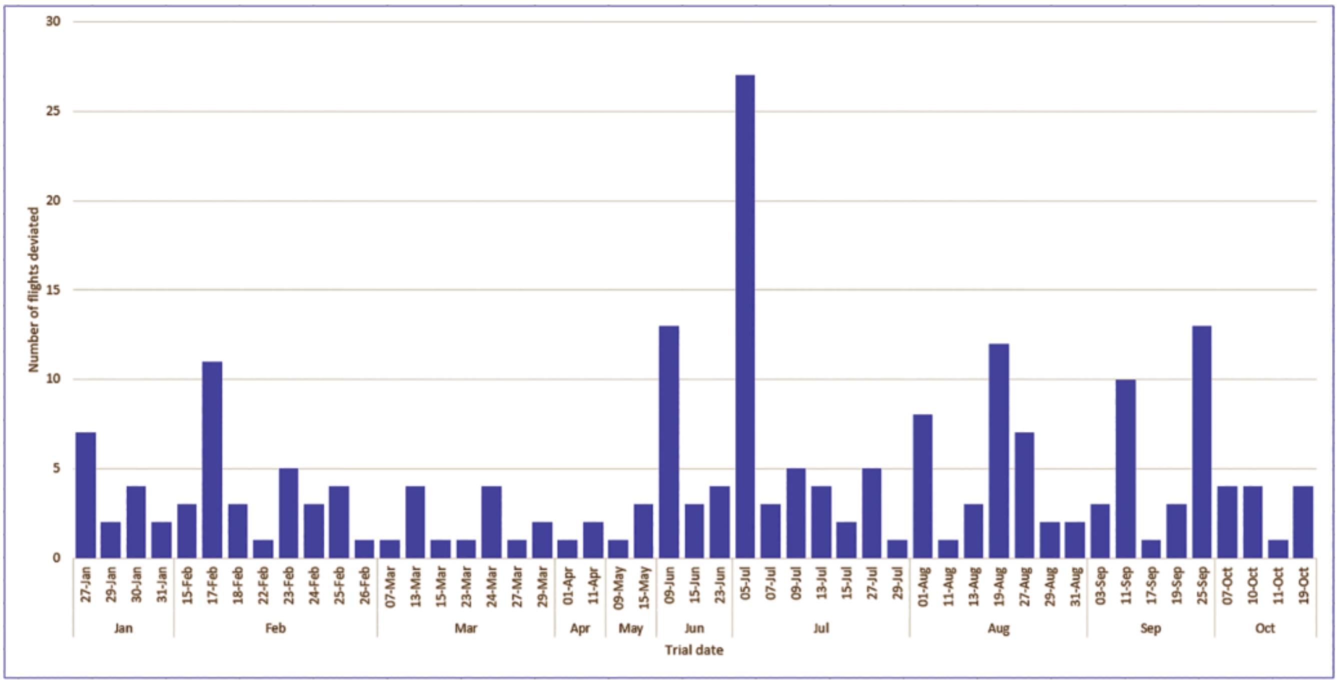

Figure A.2: Number of flights deviated daily during the trial.

have a greater effect than descending 2000 feet from the optimum altitude. The optimum altitude gradually moves higher as the flight progresses, as the aircraft gets lighter. Changing the level at the later stage of the flight is less penalising than right after departure. Depending on the distance to the Top of Descent (TOD) point, the pilot may prefer to stay on the new level rather than climb back to the original one. The operational impact of level deviations differs between aircraft types, and even among the aircraft types sharing the same ICAO aircraft type designator.

A3 Classification of trial cases

As mentioned in Section 5, every sector of the region was examined separately regarding various factors (see decision rhombuses in Fig. 5) for four hours a day and over the months of consideration. So, in total 11340 cases were investigated.

In the following the examinations of the individual factors are described in more detail:

- Rhombus “**even days**”: The data has to be separated into odd (planned aircraft diversions if possible) and even days (no actions) to compare cases with and without aircraft diversions.
- Rhombuses “**potential contrails predicted for any flight level**”: It is necessary to investigate whether potential persistent contrails are predicted or not. Therefore, all sectors were examined whether the SAC is fulfilled and ISSRs exist or not in any flight level between FL 240 and FL 450 at 17:00, 18:00, 19:00, and 20:00 UTC.
- Rhombuses “**clear sky over ISSR (t0)**” and “**clear sky in sector (t0)**”: If a sector is covered by high and optically thick ($\tau \geq 1$ at 550 nm) ice clouds, the resulting persistent contrails would not be detectable by satellite. In case of predicted potential persistent contrails, the exact horizontal location of these is examined with respect to the location of high ice clouds. If no potential persistent contrails were predicted in the sector, the entire sector was inspected for ice clouds. The time t0 refers to the time at which potential persistent contrails were predicted.
- Rhombuses “**air traffic in FL *m* and in ISSR**”, “**air traffic in sector**” and “**air traffic deviated & no other plane in ISSR**”: In addition, the flight route data have to be used to check the detected contrails. For this purpose, on days without aircraft diversions and with predicted potential persistent contrails, it is examined whether air traffic took place in a sector and within a level with predicted potential persistent contrails with a vertical tolerance range of ±10 hft (hectofeet). If there are no predicted potential persistent contrails, the entire sector is examined. In case that at least one aircraft diversion took place within a sector to avoid the formation of persistent contrails on an odd day, it has to be checked that no additional aircraft traversed a level with predicted potential persistent contrails in this sector in order to be able to clearly assign a contrail to a specific aircraft.
- Rhombuses “**linear structures detected**”: For the observation of contrails, the ones detected by the CDA one hour after the examination of the ice supersaturated regions are used, i.e., at 18:00, 19:00, 20:00 and 21:00 UTC. The reason for this is that contrails

Table A.1: Output of the classification process. The names and numbers in the green columns refer to the ovals in Figure 5. The counts are provided for the periods from February to June 2021, from July to October 2021, and for the combined period.

no action (even days)	Feb - Jun (thresh.: 100 %)	Jul - Oct (thresh.: 98 %)	total: Feb - Oct
total number	3080	2464	5544
a	106	336	442
b	194	54	248
c	150	393	543
d	1196	969	2165
no verific. possible 1	26	33	59
no verific. possible 2	166	272	438
no verific. possible 3	40	7	47
no verific. possible 4	496	235	731
no verific. possible 5	6	3	9
no verific. possible 6	24	8	32
no verific. possible 7	0	0	0
no verific. possible 8	0	0	0
CDA is incorrect 1	216	74	290
CDA is incorrect 2	0	0	0
not consi-dered 1	316	67	383
not consi-dered 2	144	13	157

aircraft deviated (odd days)	Feb - Jun (thresh.: 100 %)	Jul - Oct (thresh.: 98 %)	total: Feb - Oct
total number	3245	2551	5796
a'	3	2	5
b'	185	57	242
c'	12	6	18
d'	1562	863	2425
no verific. possible 9	0	0	0
no verific. possible 10	3	0	3
no verific. possible 11	11	2	13
no verific. possible 12	34	14	48
no verific. possible 13	0	0	0
no verific. possible 14	0	0	0
CDA is incorrect 3	0	0	0
not consi-dered 3	155	39	194
not consi-dered 4	128	15	143
not consi-dered 5	1152	1553	2705

take about an hour to expand and reach a width so that they can be seen in satellite images.

- Rhombuses "**contrails in principle observable (t1)**": To minimise misinterpretations of the CDA, the ice clouds are also evaluated at the time of the observation and detection of contrails (t1). In case contrails were observed, the exact locations of these contrails are searched for ice clouds, otherwise the entire sector.

After the examination of the factors mentioned above, each individual case ends up as a specific event (lower ellipses in Fig. 5) and the number of cases for each event is counted. The corresponding counters are shown in Table A.1.

A4 Statistical tests

In order to test whether the conditional probability for outcome ***a*** in the case where no action was taken is larger than in the case where aircraft were deviated, we performed several statistical tests. Two of them are displayed in the following: (i) a one sided two-proportion z-test and (ii) a pair of independent z-tests for the value of the conditional probabilities for outcome ***a*** (without and with action).

In test (i) the null hypothesis is:

- H_0: The conditional probability for outcome ***a*** in the case where no action was taken is smaller than in the case where aircraft were deviated.

Performing this test with the data of Table 2 results in a rejection of the null hypothesis with a statistical error of 2.5 %. Hence, we can accept the alternative hypothesis, i.e., the conditional probability for outcome ***a*** in the case where no action was taken is larger than in the case where aircraft were deviated.

As a side product, this test gives a 95 % confidence interval ranging from appr. 6 % to 41 % (percent points) for the difference between the two probabilities.

In test (ii) we choose a statistical error of 5 % and test the following pair of independent null hypotheses:

- H_0 (no action): The conditional probability for outcome ***a*** is less than 42 %;

- H_0 (aircraft deviated): The conditional probability for outcome ***a*** is larger than 39 %.

The result is to reject both null hypotheses with a 5 % statistical error, i.e., the outcome ***a*** (potential persistent contrails predicted and persistent contrails observed) has a probability of more than 42 % if no action is taken, but a probability below 39 % if flights are deviated.

If we perform a similar test (ii) with only the data of the first period, i.e., from February to June, we arrive at a similar result, however only at a significance level of 10 %. If we consider only the data from July to October, the significance level would be 15 %. This is caused by the low number of counts for the "aircraft deviated" cases, see Table A.1.

Data Availability Statement

Satellite data are freely available after registering with EUMETSAT. DWD provides the WAWFOR weather forecasts, such as wind, temperature and relative humidity, directly only to customers that pay for this service. However, the data are also available via the open data server of DWD, however not on flight levels. Detailed information about flight trajectories and MUAC instructions are archived by Eurocontrol MUAC and can be requested within the terms of general data protection regulations. Access is possible on request in cases of well justified legal purposes. On request, the code for calculating ice super-saturated regions can be provided by klaus.gierens@dlr.de.

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