Advancing the Science for Aviation and Climate

ACACIA

Deliverable 2.2

Title: Report on statistics of instantaneous radiative forcing and meteorological conditions where the strongest contrails appear

Lead partner: DLR, FZJ

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0   Summary

This deliverable first presents the effect of weather variability on the instantaneous radiative forcing of persistent contrails. This investigation was intended to give an answer to the question why the uncertainty of global/annual contrail RF or ERF that is presented in IPCC-style charts, does not become significantly smaller since the 1999 special report on Aviation and the Global Atmosphere, in spite of considerable progress in modelling and observational capabilities. This study has already been published in an open access journal and only a summary of these results is given here. One important message is that the safest operational mitigation option for contrails is to concentrate on those that have the strongest endothermic (warming) effect.

The second part of this deliverable thus presents first results on the weather (synoptic) and ambient conditions that favour the formation of very strong endothermic contrails. This is work in progress. We hope that these investigations enable a reliable prediction of such situations for the purpose of the mentioned mitigation strategy.

1 Statistics of instantaneous radiative forcing

The research to this topic has recently been published in an open access paper. Its content is summarized below, the main message is given as well as the citation and link to the publication.

1.1 Abstract of the paper "Weather Variability Induced Uncertainty of Contrail Radiative Forcing"

Persistent contrails and contrail cirrus are estimated to have a larger impact on climate than all CO_2 emissions from global aviation since the introduction of jet engines. However, the measure for this impact, the effective radiative forcing (ERF) or radiative forcing (RF), suffers from uncertainties that are much larger than those for CO_2. Despite ongoing research, the so-called level of scientific understanding has not improved since the 1999 IPCC Special Report on Aviation and the Global Atmosphere. In this paper, the role of weather variability as a major component of the uncertainty range of contrail cirrus RF is examined. Using 10 years of MOZAIC flights and ERA-5 reanalysis data, we show that natural weather variability causes large variations in the instantaneous radiative forcing (iRF) of persistent contrails, which is a major source for uncertainty. Most contrails (about 80%) have a small positive iRF of up to 20 W m^{-2}. IRF exceeds 20 W m^{-2} in about 10% of all cases but these have a disproportionally large climate impact, the remaining 10% have a negative iRF. The distribution of iRF values is heavily skewed towards large positive values that show an exponential decay. Monte Carlo experiments reveal the difficulty of determining a precise long-term mean from measurement or campaign data alone. Depending on the chosen sample size, calculated means scatter considerably, which is caused exclusively by weather variability. Considering that many additional natural sources of variation have been deliberately neglected in the present examination, the results suggest that there is a fundamental limit to the precision with which the RF and ERF of contrail cirrus can be determined. In our opinion, this does not imply a low level of scientific understanding; rather the scientific understanding of contrails and contrail cirrus has grown considerably over recent decades. Only the determination of global and annual mean RF and ERF values is still difficult and will probably be so for the coming decades, if not forever. The little precise knowledge of the RF and ERF values is, therefore, no argument to postpone actions to mitigate contrail's warming impact.

1.2 Selected results

Here we present the probability density function of the instantaneous radiative forcing of persistent contrails (Figure 1) and the so-called first-order effect function.
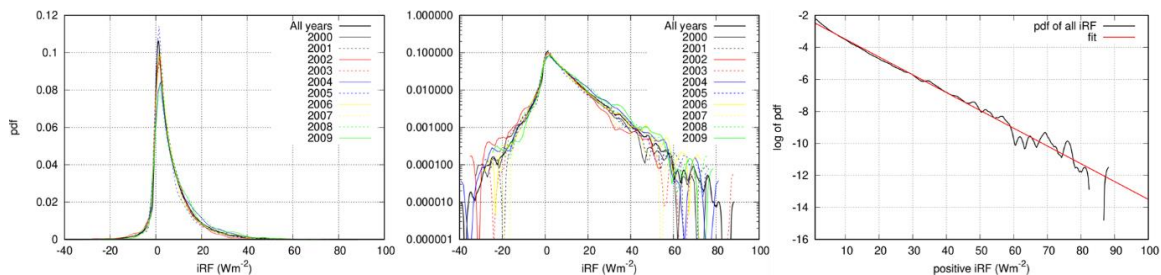

Figure 1: Probability density function for instantaneous radiative forcing of persistent contrails. Left: the pdfs for each of 10 years of data (2000-2009) and for the whole decade. Middle: the same, but as half-logarithmic plot, highlighting the exponential nature of the upper tail. Right: the upper tail with a fitted exponential function.
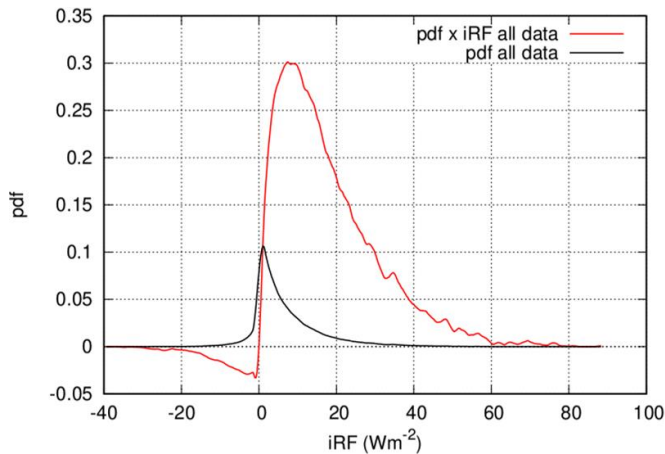
Figure 2: Probability density function (black) and first-order effect function (red) for instantaneous radiative forcing of persistent contrails. The first-order effect function is the product of the effect size (i.e. iRF) with its probability (or frequency of occurrence). It shows the impact of strong contrails much clearer than the pdf alone.

1.3 Take away messages

1) Despite of ongoing research the error bar or uncertainty in contrail RF does not get smaller.
2) Weather and other variabilities produce a very broad pdf of contrail iRF (which finally sum up to the global/annual integrated RF). These variabilities are irreducible.
3) Strong endothermic contrails produce the major share of the overall warming impact of contrails.
4) Thus it is the safest mitigation strategy to avoid formation of strong endothermic contrails (Big Hits); these are strong enough so that any uncertainties do not entail the danger that the measure leads to perverted results (e.g. it is quite sure that these are not actually cooling contrails)

Even though most persistent contrails produce iRF in the range of 0 to 20 W m^{-2}, strong contrails with iRF>20 W m^{-2} still happen in about 10% of all cases. Extreme value theory lets us assume that actually the highest values of iRF could exceed the upper range of the present dataset. Their overall endothermic effect on climate is disproportionate, and proceeding from iRF to the energy forcing, the properly relevant quantity in this respect, would stress the impact of strong contrails even further. This is why an aspiration for the capability of numerical weather forecast models to predict the strong endothermic contrails is justified and timely.

1.4 Reference and link

Wilhelm, L., K. Gierens, S. Rohs, 2021: *Weather Variability Induced Uncertainty of Contrail Radiative Forcing.* Aerospace, 8, 332. doi:10.3390/aerospace8110332.
(https://www.mdpi.com/2226-4310/8/11/332/pdf)

2 Meteorological conditions where the strongest contrails appear

This section describes ongoing research that has the final goal enable the reliable prediction of situations where strong endothermic contrails can form. If this were known with sufficient confidence before flight planning or at least before the start of a flight, the flight could be routed to avoid such regions. Since strong contrails are rare phenomena, the need for additional fuel and the emission of extra CO_2 can be minimized by such a strategy.

2.1 Comparison of conditions for situations with and without strong contrails

Our research strategy starts with a comparison of the distributions (probability densities) of meteorological properties of the ambient atmosphere in situations where strong endothermic contrails form (acc. to the MOZAIC data) and where not. If these distributions were totally distinct, the flight planning to avoid strong contrails would be easy. Of course, life isn't that easy; the pdfs overlap more or less strongly. But taking a variety of quantities into account, it may be possible to characterize Big Hit situations more distinctly and to distinguish them from other situations where contrails are weak or even exothermic (cooling).

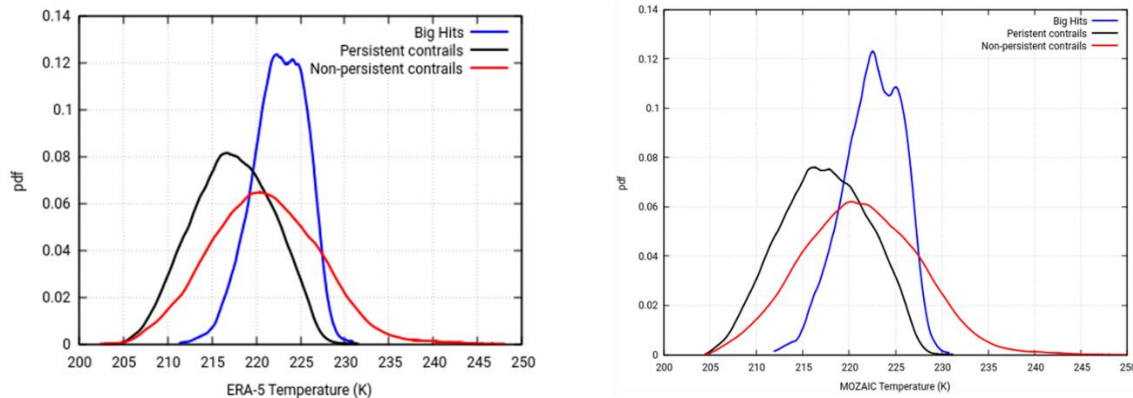### 2.1.1 Thermodynamic quantities temperature, relative and absolute humidity

Figure 3: Temperature distribution in general situations (red), in situations that allow persistent contrails (black) and in situations with very strong endothermic contrails (Big Hits, blue). Left panel shows the situation as seen from ERA-5 reanalysis data, right panel the same with MOZAIC data. Note that the criteria whether persistent contrails or whether even Big Hits are allowed are based on the measurement data, i.e. on MOZAIC.

There are clear differences in the temperature distributions (Fig. 3) for the 3 considered situations: general (no contrails or only short contrails), situations with persistent contrails acc. to MOZAIC data (i.e. Schmidt-Appleman criterion fulfilled and ice supersaturation), and Big Hits (i.e. iRF > 20 W m^{-2}). The existence of a temperature threshold for contrail persistence causes the temperature distribution for persistent contrail situations to be centred on lower temperatures than under general conditions, but Big Hits are found rather at the high end of that distribution. This is explained by the fact that absolute humidity (that is the water mass that can be converted into ice) generally increases with temperature and indeed the highest absolute humidity values in our data are found in Big Hit situations (Fig. 5). Fig. 4 reflects in the MOZAIC version that contrail persistence and Big Hits needs at least ice saturation at formation. This is not reflected in the reanalysis data since the humidity forecast in the numerical weather prediction model is not perfect.
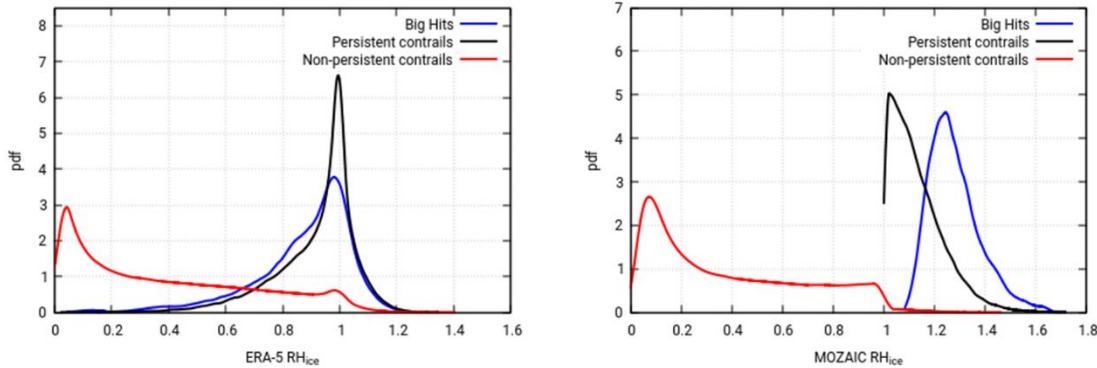
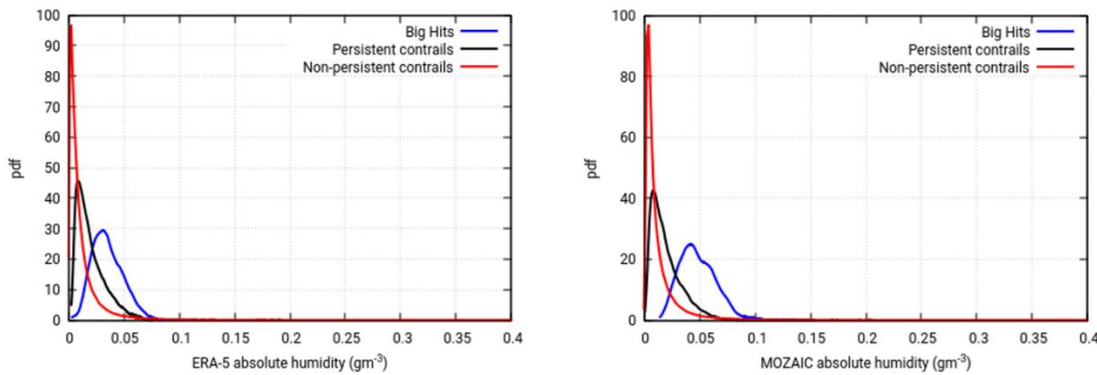**Figure 4: As figure 3, but for the relative humidity with respect to ice.**

Figure 5: As figure 3, but for the absolute humidity.

2.1.2   Dynamical characteristics

The dynamical quantities have all be obtained from the ERA-5 reanalysis, interpolated to the position and time of the corresponding MOZAIC data. There are more or less large differences in their distributions.

Vertical velocities are centred close to zero, in particular for the general situation, which is expected. But ice supersaturation is often a consequence of rising and thus cooling air. This is visible in Figure 6, top left, where the corresponding distributions are slightly shifted to a negative mode value and where they have a broader negative tail. Note that the vertical motion is given in pressure coordinates, that is negative values indicate upward motion.

Close to the tropopause in the upper troposphere (that is, in usual cruise altitudes) upward motion hits a "rigid" boundary and must therefore spread outward. This is signified by positive divergence (Fig. 6 top right). Evidently, the distributions for peristent contrails and Big Hits are slightly shifted to positive values compared to the reference of the general situation.

For the vorticity (Fig. 6 bottom left) there is a quite distinct difference between persistent contrail and general cases. Contrails, like their parent ice-supersaturated regions, prefer negative vorticity, that is airmasses that rotate clockwise on the northern hemisphere.

Ice supersaturation is most frequent below the tropopause, but rare above it. The tropopause can be approximately identified with a potential vorticity of 2 PVU. In our data, we find therefore most persistent contrails and Big Hits in locations with PV below 2 PVU, which is not so for the general situation where also stratospheric values (PV>2 PVU) occur often (Fig. 6, bottom right).
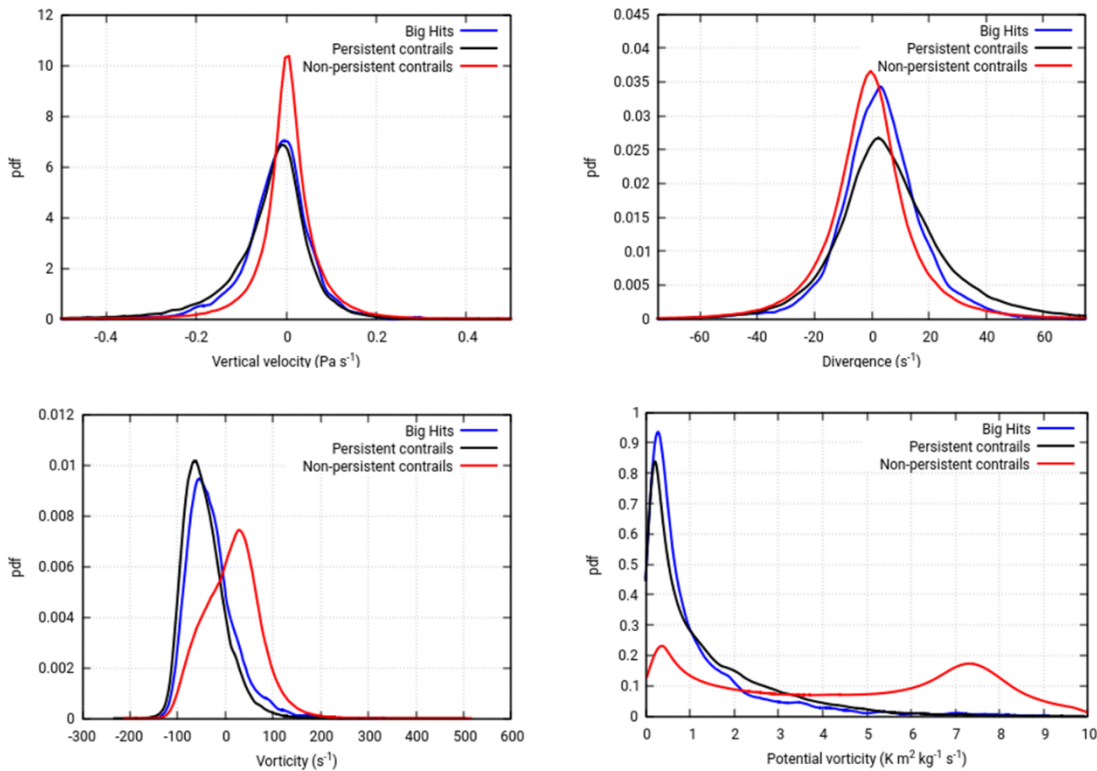
Figure 6: Dynamical characteristics of situations that allow contrail persistence (black) and even Big Hits (blue). For reference, the distributions in the general situation are given as well (red).
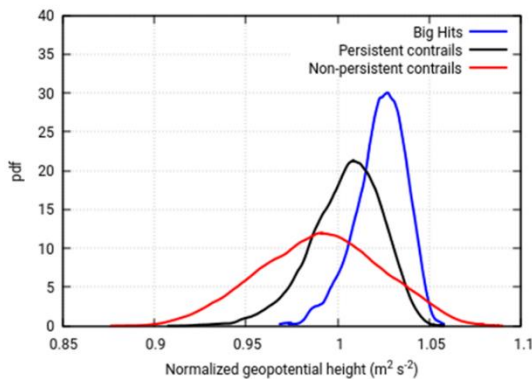

Figure 7: The distribution of the normalized geopotential height for general situations (red), persistent contrails (black) and Big Hits (blue)

The normalized geopotential height is defined such that it measures the relative distance from a nominal height of each pressure level. Z=1 means that the pressure level has its nominal geopotential height, Z>1 implies an excursion to higher altitudes and vice versa. We use it for a better comparison of the geopotential on different pressure levels.

Obviously, persistent contrails and Big Hits are on average found on the top altitudes of the pressure levels, but rarely on the lower altitudes (see Fig. 7).

Finally, we consider the lapse rate (that is, the vertical temperature gradient) in the three considered domains. The lapse rate is related to the stability of the stratification of the airmasses. A high lapse rate of nearly 10 K km^{-1} signifies a neutral stratification, whereas smaller values imply stable stratification. The mean lapse rate in the troposphere is about 6.5 K km^{-1}. Negative lapse rates occur when there are temperature inversions (temperature increasing upwards). This happens here when the tropopause is close to the flight level. Fig. 8 shows that the stratification is much weaker at locations with contrails and Big Hits than elsewhere, a fact, that is not yet understood.
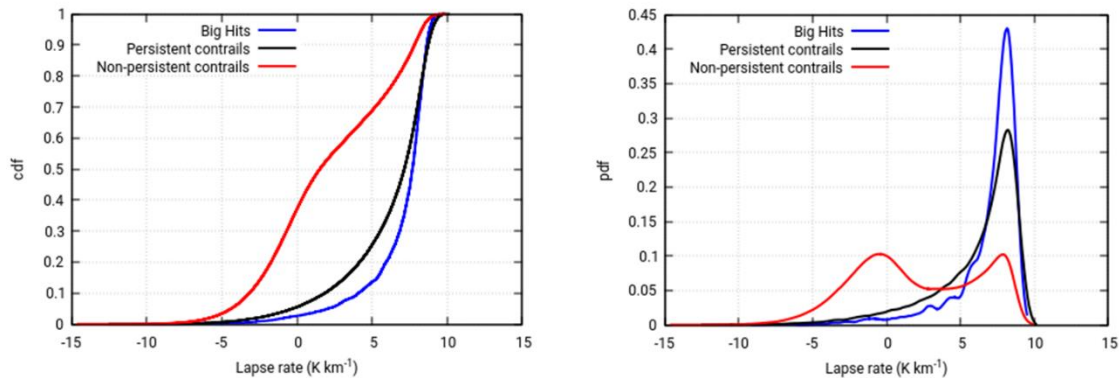

Figure 8: Left: Cumulative distribution function of lapse rates for the 3 different classes as before. Right: The same, but shown as probability density functions (i.e. the derivatives of the curves on the left).

2.2   Final remarks, plan for publication

Obviously, some quantities differ less, some more distinctly between the general no- or short contrail situation (relative humidity below ice saturation) and situations where contrail persistence and Big Hits are possible. Often the distributions for Big Hits differ more from the general distributions than the distributions for persistent contrail situations do (exception: temperature). Thus, it might be possible to base a prediction for contrail persistence and Big Hits on an appropriate combination (regression or neural network) of dynamical quantities. Another quantity that is important for such a purpose is the position of the sun, since contrails don't cool during night, and this simple fact should be exploited when a prediction method is constructed.
As stated above, this is ongoing work. A publication of these results is planned for the near future.

Both parts of this work will constitute Lena Wilhelm's master thesis.