Statistics of potential radiative forcing of persistent contrails

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Introduction

Contrails affect climate if they are persistent, that is, if they are located in an ice-supersaturated region (ISSR). They do this by reflecting sunlight back to space (cooling) and by blocking thermal radiation from the Earth surface and lower atmosphere (warming). These two effects, the short-wave and long-wave radiative forcings (RFSW and RFLW), have individually relative large values (see below), but the net effect, RF, is their difference and as such has a much larger uncertainty than the individual components (Gaussian error propagation). RF is a measure for the immediate radiative impact of a contrail. A negative value means that the short-wave cooling effect dominates while a positive value signifies a net warming. During night, there is always net warming since sunlight and thus it's possible reflection is absent.

In most (daytime) cases (see below) there is substantial cancellation of the warming and cooling effects, but occasionally (in particular during night) the long-wave warming effect dominates such that the respective contrail has a particularly strong contribution to climate warming. This is a Big Hit, and such contrails should be avoided already in the flight planning phase. Such an avoidance strategy needs of course a reliable prediction of the conditions under which contrails actually are that strong climate warmers.

The topic of this presentation is how situations with strong warming contrails can be characterised and whether and how reliably it is possible to predict them.

Method and data

For the present evaluation we use forecast data from the ERA-Interim Reanalysis. We use forecasts valid at 1-30 April 2006, 3-24 h in 3 h steps and all initialised at midnight each day. The analysis is confined to pressure levels 200, 250, and 300 hPa. The study region is 40°W to 20°E and 30 to 60°N. The data are used in $1^\circ \times 1^\circ$ spatial resolution.

First, temperature and relative humidity are used to check whether contrails are possible, applying the Schmidt-Appleman criterion (Schumann 1996) assuming an overall propulsion efficiency of 0.35. If contrails are indeed possible it is further checked whether there is ice supersaturation. As ISSRs (ice supersaturated regions) appear implausibly patchy if the real condition for ISS, namely $RHi > 100\%$ is used, we apply a correction of 5% and define ISSRs as regions with $RHi > 95\%$. All computations of water vapour available for condensation take this 95% as base value.

For grid points where persistent contrails are possible their potential optical thickness is computed assuming a geometrical thickness of 500 m, and assuming that all humidity in excess of $RHi > 95\%$ is converted to ice crystals with an effective radius of 30 μm. The calculation uses the parameterisation of Ebert and Curry (1993). The optical thickness of nearby natural cirrus is computed directly from the forecast ice water content values, assuming a cloud thickness of 1500 m and an effective crystal radius of 60 μm.

The calculation of shortwave and longwave radiative forcing is done using the parameterisation given by Schumann et al. (2012) applying the parameters for so called Myhre particles. This and other simplifications mentioned above are justified since the goal here is not to compute radiative forcing *per se* but to see whether and how particularly strong values of RF are related to meteorological quantities that characterise the nearby situation. To this end it suffices that RF values are mathematically ordered; their magnitude is irrelevant.

For this reason it is also in order to compute the radiative forcing values for 100% coverage.

Results

Plausibility tests

The results of the study are represented in scatter plots showing for each grid point and for all days and time steps where a persistent contrail would be possible the potential radiative forcing versus one of the meteorological quantities. The different pressure levels are distinguished by different colours: black, red, and blue for 300, 250, and 200 hPa, respectively.

In table 1 we list a couple of overall statistical key figures, viz. minimum, maximum, mean and standard deviation of a number of quantities. From the table one sees that the negative shortwave forcing can have a larger magnitude (here $96.6\,\mathrm{W\,m^{-2}}$) than the positive longwave forcing (here $75.9\,\mathrm{W\,m^{-2}}$). In spite of this, the mean longwave exceeds the mean shortwave forcing in magnitude and the mean net forcing is positive under all considered circumstances. The effect of nearby natural cirrus on the forcing is rather small, both in the extreme values and the mean. However, contrails appear to have a larger amplitude of RF when nearby cirrus clouds are thicker and vice versa. However, the overall mean appears relatively insensitive to all these situations. It is worth noting that the extremes in both directions are one and a half orders of magnitude larger than the mean forcings.

Contrails in our data set have optical thicknesses ranging from practically zero to 1.21. This is a plausible range, consistent with values reported in literature. A mean value of 0.10 is consistent with literature values as well, although higher values (~ 0.3) have been reported occasionally.

Figure 1 shows potential radiative forcing versus contrail optical thickness τ. Not surprisingly, the range of possible RF values increases with τ. The range of optical thickness increases

quantity	min	max	mean	std. dev.
RFSW	−96.6	0.0	−3.5	5.9
RFSW (day only)	−96.6	0.0	−5.3	6.5
RFLW	0.0	75.9	6.6	7.1
RF incl. nat. Ci	−32.5	74.2	3.1	5.3
RF excl. nat. Ci	−14.0	59.3	2.4	4.3
RF, IWC$>1\,\mathrm{mg\,m^{-3}}$	−32.5	74.2	3.3	5.7
RF, IWC$<1\,\mathrm{mg\,m^{-3}}$	−29.5	59.2	2.9	4.9
τ all	0.0	1.21	0.10	0.11
τ ($\tau_c = 0$)	0.0	1.01	0.06	0.07
τ ($\tau_c > 0$)	0.0	1.21	0.11	0.12
τ_c	0.0	5.97	0.13	0.22

Table 1: Some statistical key figures. Shortwave, longwave and net radiative forcing for all sky conditions assuming 100% coverage in regions where persistent contrails are possible, and radiative forcing for the hypothetical case without natural cirrus clouds around. Further, RF in regions of Ci with IWC$>1\,\mathrm{mg\,m^{-3}}$ and IWC$<1\,\mathrm{mg\,m^{-3}}$. Optical thickness of persistent contrails assuming 500 m geometrical thickness, generally and in situtations with and without nearby cirrus. The optical thickness distribution of the natural cirrus is given in the last line. There are a total of 186329 potential contrail cases in the study set.

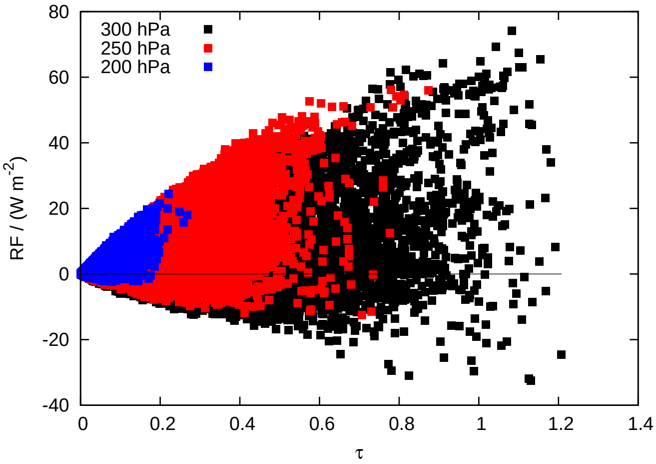


Figure 1: RF vs τ.

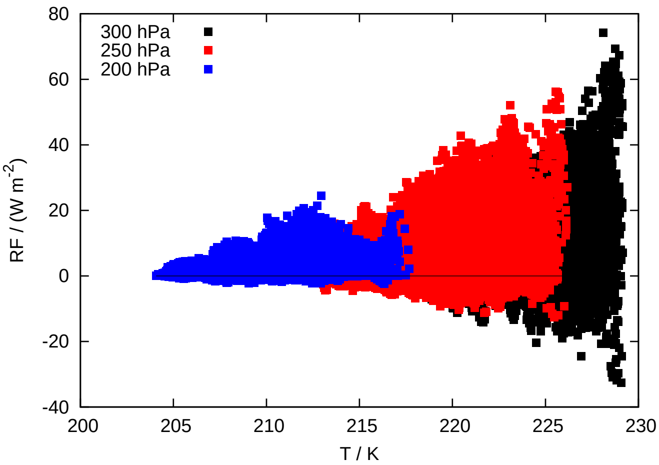


Figure 2: RF vs T.

with atmospheric pressure because temperature, absolute humidity and thus condensable humidity increase with atmospheric pressure. For the same reason, the RF range increases with temperature, as shown in Fig. 2.

Figure 3 shows that the RF range increases also with relative humidity, but the pressure level has — via temperature and absolute humidity — the stronger influence.

The effect of nearby natural cirrus on RF is seen in Fig. 4. The thicker the cirrus the narrower is the range and the smaller is the magnitude of RF. Contrail forcing approaches zero when thick cirrus is around. Note however, that the largest amplitude of RF is found when there is some cirrus around. Probably, without any cirrus there is usually also little supersaturation such that contrails tend to be optically thinner without cirrus than with such clouds around. This is confirmed by the values given in the table: without natural cirrus ($\tau_c = 0$) both maximum and mean optical thickness of contrails are smaller than with cirrus ($\tau_c > 0$).

During night all contrails contribute to climate warming, but during daylight both warming and cooling is possible. Figure 5 shows the distribution of RF values for the range of solar zenith angles (SZA) that are possbible during April in our region. The figure shows that the largest

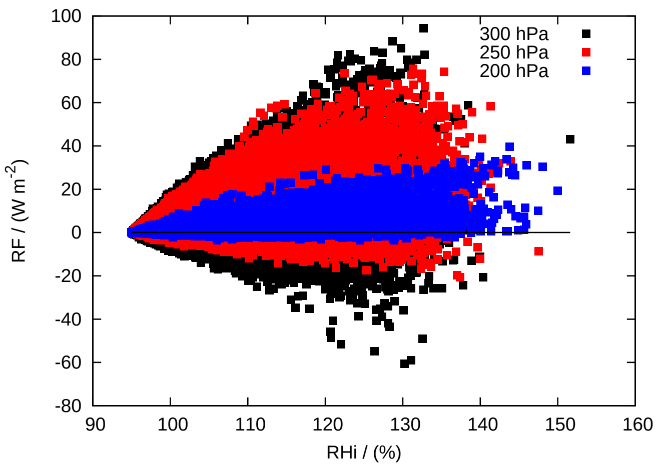


Figure 3: RF vs RHi.

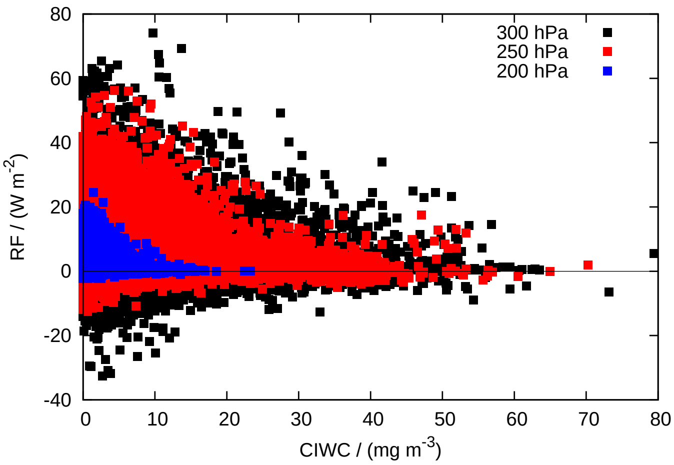


Figure 4: RF vs cloud ice water concentration (CIWC).

cooling events occur in the middle of the cos(SZA) range. According to the results of Meerkötter et al. (1999), the strongest SW forcing occurs at zenith angles of 60-70°. So the present results are in principle consistent with the old ones. Here we find strong positive forcings when the SZA exceeds 70° since this implies that the solar direct radiation approaches zero. However, diffuse solar radiation which is not a factor in Schumann's parameterisation could add some SW forcing at low sun. Thus RF values for large SZA are probably overestimated.

So we find in general plausible results. An important observation is that large values of RF in certain regimes of the considered quantities (e.g. at high temperatures) are always accompanied with low and even negative values. So far we did not find a unique relation between a meteorological quantity and RF. We found only that the *range* of possible RF values is small and around zero in one extreme of the quantities and large in the opposite extreme. In other words, it is not possible to predict Big Hits by considering just one meteorological quantity.

The statistical distribution of potential RF

Figure 6 shows on top the cumulative distributions of RF for the three considered pressure

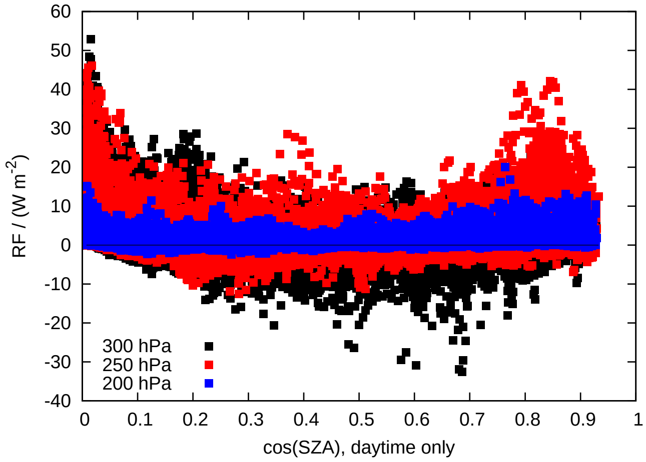


Figure 5: RF vs cos(solar zenith angle), daytime only.

levels. They have similar shape (nearly exponential in the positive range), but different widths, getting wider towards lower altitude, consistent with the results shown earlier (Figs. 1-3). The figure demonstrates that most persistent contrails are warming. It suffices to read the cdf-values at RF=0. These are 0.24 for the 300 hPa layer, 0.16 for 250 hPa and 0.09 for 200 hPa. This means for instance that on 300 hPa only one quarter of all contrails are cooling, while three quarters contribute to warming the climate. It seems as if the partitioning between cooling and warming contrails is shifted towards warming ones on flying higher, which is consistent with lower temperatures and thus higher infrared contrast on higher flight levels. However, this does not imply a recommendation of flying lower, as seen in the following.

The middle part of Fig. 6 shows the correpsonding probability densities, $f(RF)$, and the product $RF \cdot f(RF)$, quasi the density of the first moment. The latter can be interpreted as a measure of the first order impact of a situation with a certain RF, namely the frequency with which such an RF occurs times the size of that event (that is, RF itself). This measures quasi the instantaneous effect. Obviously, the Big Hits occur most often on the lowest of our three pressure levels, because the temperature and thus absolute humidity is highest there. Thus, although the fraction of warming contrails is lowest on the lowest of our three levels, they have the largest impact individually. Also the cooling contrails are strongest on the lowest level. So it is better to fly lower if the contrails are expected to cool, but to fly higher if they are expected to warm, in particular during night.

If one assumes that contrail lifetime and coverage scale as well somehow with RF, say with RF^a and RF^b, $(a, b > 0)$ then we could measure the total effect with RF^{1+a+b}. But there are no indications so far in this direction, and I do not wish to speculate. Anyway, it is evident that the most probable values (mode values) of RF on all pressure levels are only slightly positive, more than one order of magnitude smaller than the corresponding maxima. However, taking the first order effects into account shows that the much rarer big events contribute substantially to the overall (instantaneous) effect. This will be the more so if we could also take lifetime and width of such contrails into account.

Finally, we compute

$$\frac{\int_0^x RF \cdot f(RF)\,\mathrm{d}\,RF}{\int_0^\infty RF \cdot f(RF)\,\mathrm{d}\,RF}$$

which is the cumulative first order effect of warming persistent contrails up to an RF value

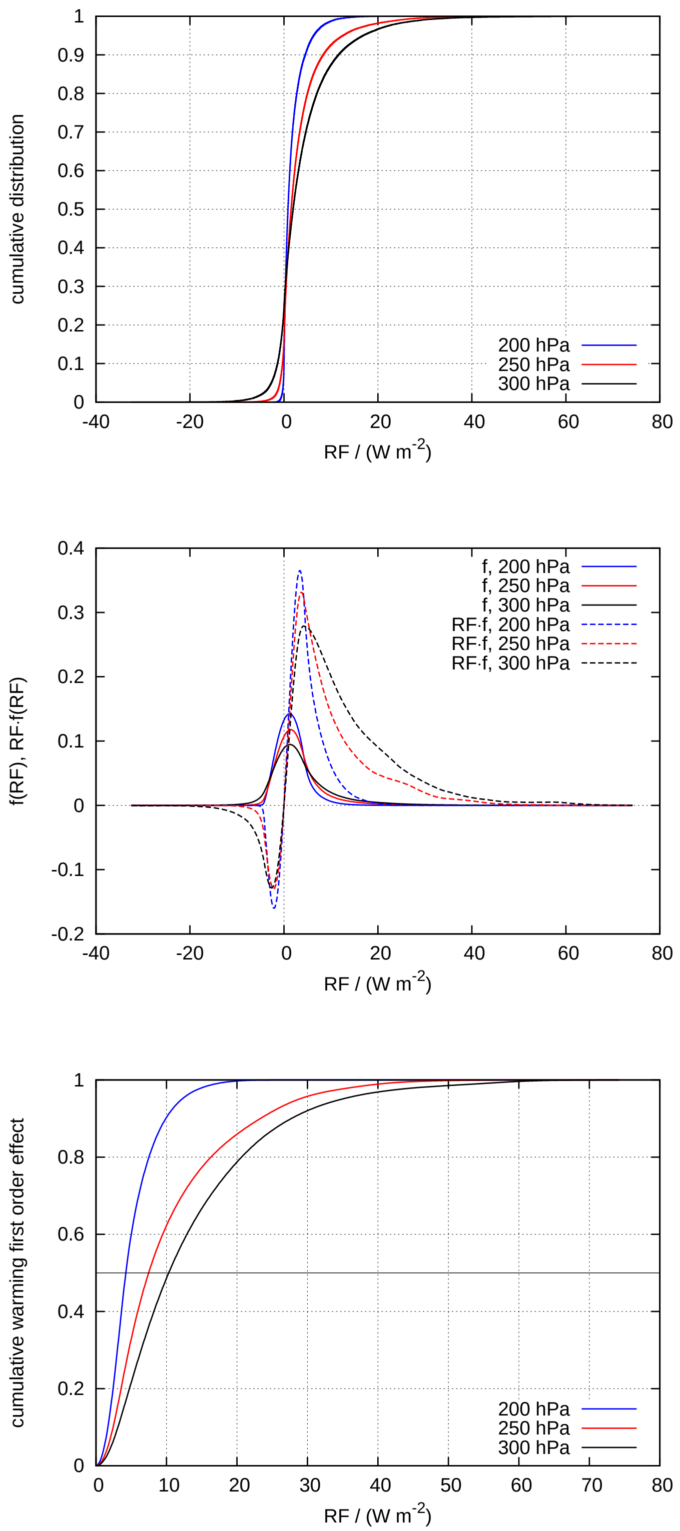


Figure 6: Top: Cumulative distribution of potential RF on three pressure levels. The distributions have similar shape but they get wider on lower levels. If the analysis is restricted to non-negative values of RF, exponential distributions can be fitted quite well. Middle: Corresponding probability density functions (solid) and 1st moment functions (dashed). The latter is the frequency with which a certain RF occurs multiplied with that RF, which is a measure for a first order effect. Bottom: Integral of $RF \cdot f(RF)$ (the first order effect) for positive values of RF only, that is, for warming cases. The horizontal line serves to mark the median values of the first order effects. Effects above the median can be considered Big Hits.

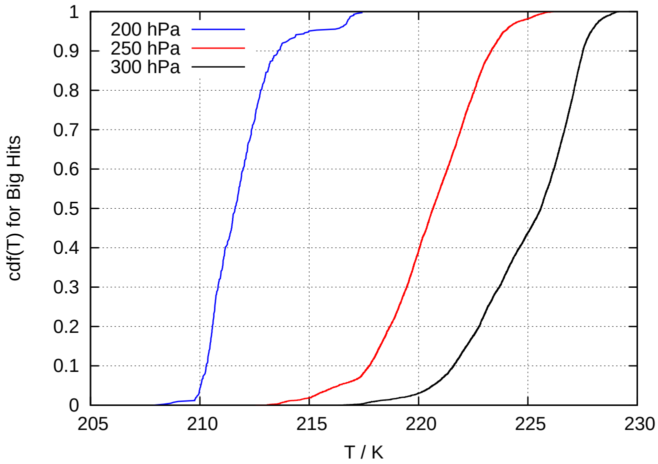


Figure 7: Cumulative distribution of T for Big Hits (potential contrails with $RH > 10\,\mathrm{W\,m^{-2}}$).

of x. The result is presented for the three pressure level in the bottom panel of Fig. 6. The horizontal line is added to mark median values which mean that half of the first order warming effects are caused by cases with RF values higher than the median. These median values are: $4.2\,\mathrm{W\,m^{-2}}$ for 200 hPa, $7.5\,\mathrm{W\,m^{-2}}$ for 250 hPa, and $10.3\,\mathrm{W\,m^{-2}}$ for 300 hPa. We may now take these values to define Big Hits. In the following, however, I want to keep the discussion simple; I want to avoid three different thresholds and take thus only one for all pressure levels. I choose a threshold value of $10\,\mathrm{W\,m^{-2}}$; contrails with an RF exceeding that value are thus considered Big Hits in the following.

The Big Hits

Contrails with an RF in excess of $10\,\mathrm{W\,m^{-2}}$ occur in 8.1% of our potential contrail cases, but they contribute quite substantially to the first order impact, as seen in Fig. 6. The higher a flight occurs the lower is the probability to produce a Big Hit contrail.

Let us now study how the occurrence of a Big Hit depends on the quantities that are input to Schumann's formulas, that is, temperature, optical thickness of contrail and ambient cirrus, and radiation quantities.

Figure 7 shows the cumulative distribution of temperature for Big Hit situations on the three pressure levels. Most Big Hits occur in those temperature ranges where the corresponding curves are steep (the corresponding probability density obtains maxima there). It was already evident in Fig. 2 that temperatures that allow Big Hits do not exclude weak and even cooling contrails. This finding is reflected here. Big Hits do not occur at the coldest temperatures of each level (for instance not below 207 K on 200 hPa).

Similarly, Big Hits need a minimum optical thickness of about 0.1 of the contrails, see Fig. 8 (top). From the entries in table 1 we see, that this is just the average value. Ambient cirrus must not be too optically thick (see bottom panel). On 200 hPa there are no Big Hits when ambient cirrus with $\tau_c > 0.1$ is present, a quite small value. On the two lower levels these thresholds are larger, about 0.6 for 250 hPa and 1.0 on 300 hPa. The flat part of the curves indicates ranges of τ_c where the occurrence of Big Hits is improbable because the ambient cirrus is relatively optically thick which diminishes any contrast in thermal radiation between a contrail and its environment.

In Fig. 9 we see for the first time a night-day difference. Night cases are collected at the respective zero values of both μ (cosine of solar zenith angle) and a_{eff}, the effective albedo.

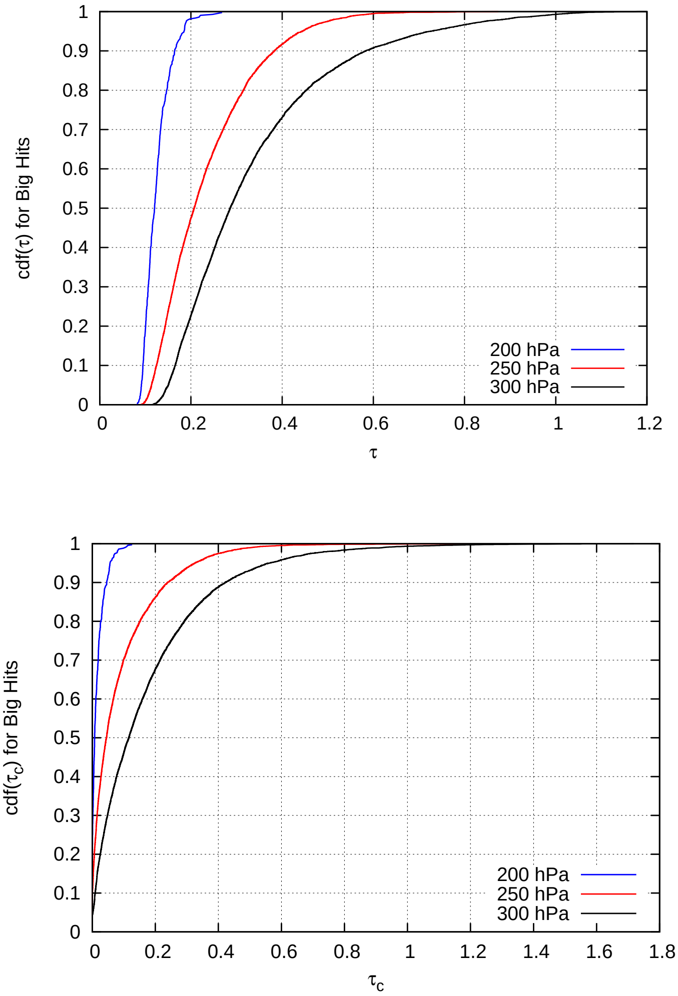
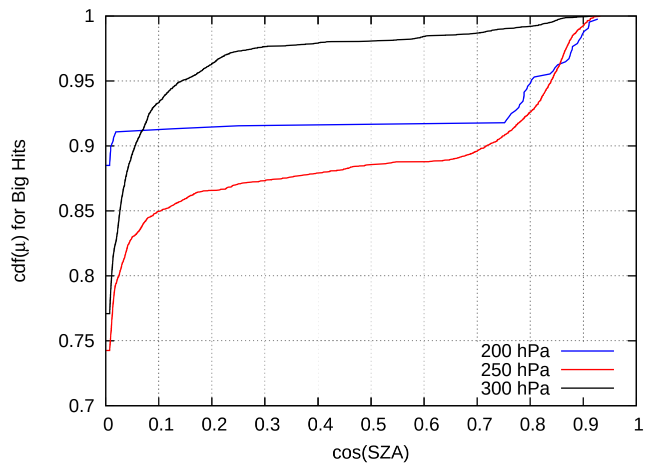


Figure 8: Cumulative distribution of τ and τ_c for Big Hits. Note the different scale on the x-axis of the two plots.

Obviously most Big Hits occur at night, more than 70% generally and almost 90% on the uppermost of the considered levels. This is a lucky situation since it is much easier to reroute aircraft at night for contrail avoidance than during daytime when traffic is much denser than at night. During daytime Big Hits occur preferentially when the sun is low or when it is high, but not at intermediate sun angles. As discussed before, the RF values at low values of μ could be overestimated to an uncertain degree, because diffuse solar radiation is not represented in Schumann's parameterisation.

The outgoing longwave radiation (OLR, see top of Fig. 10) is preferentially in a medium range, about 180 to 320 $\mathrm{W\,m^{-2}}$ out of a total range in our data of about 131 to 355 $\mathrm{W\,m^{-2}}$, when there are Big Hits. The range depends a bit on the considered pressure level (or flight altitude). That is, we expect no Big Hits when OLR is either at its low end (very cold background) or its high end (very warm background). The latter is a bit surprising since a warm background favours a strong temperature contrast between the contrail and the background, thus a large longwave effect. But it may simply be that these high OLR values occur rarely, then it is no surprise that only few Big Hits occur at such OLR values.

The reflected solar radiation (RSR, bottom of Fig. 10) varies in general between zero (night)



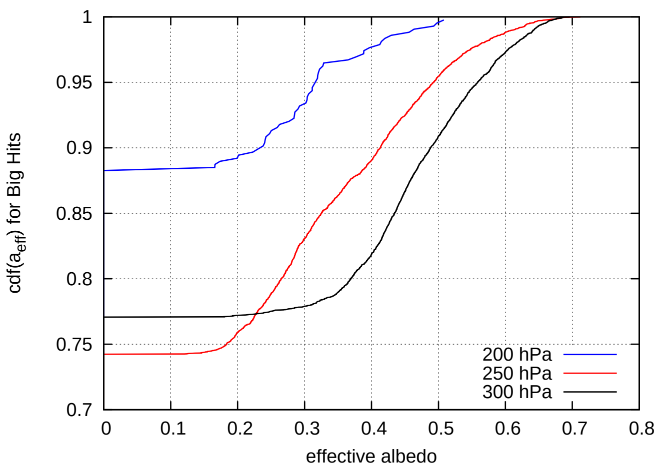


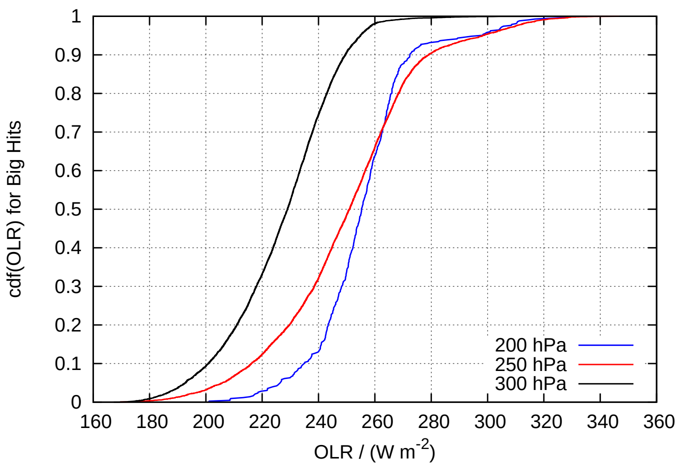
Figure 9: Cumulative distribution of $\mu = \cos(\mathrm{SZA})$ and a_{eff} for Big Hits. The value at $\mu = 0$ or $a_{\mathrm{eff}} = 0$ represents the contribution of night cases, which are generally more than 70%.

and 736.1 W m^{-2} in our data. The figure shows that Big Hits occur predominantly when RSR is very low, consistent with the finding that they occur at very flat sun angles (perhaps overestimated as discussed above). The cdf curves look very differently for the three pressure levels and it is difficult to obtain further general information from these curves. Note that these curves are filtered for day cases only.

Conditional probabilities related to Big Hits

The following calculations serve the purpose to get a feeling of situations that are prone to Big Hits without the necessity to perform calculations with Schumann's formulas. Such a qualitative feeling can be obtained from conditional probabilities of the form $P(BH|X = x \pm \Delta x)$ which is the probability to get a Big Hit in a situation where a certain quantity X obtains a value in the range $[x - \Delta x, x + \Delta x]$. All situations that we consider are conditioned on the fulfillment of the Schmidt-Appleman ($SAC = 1$) criterion and on ice supersaturation ($ISS = 1$) such that our conditional probabilities are proper

$$P(BH|X = x \pm \Delta x) = P(BH|X = x \pm \Delta x \wedge SAC = 1 \wedge ISS = 1).$$



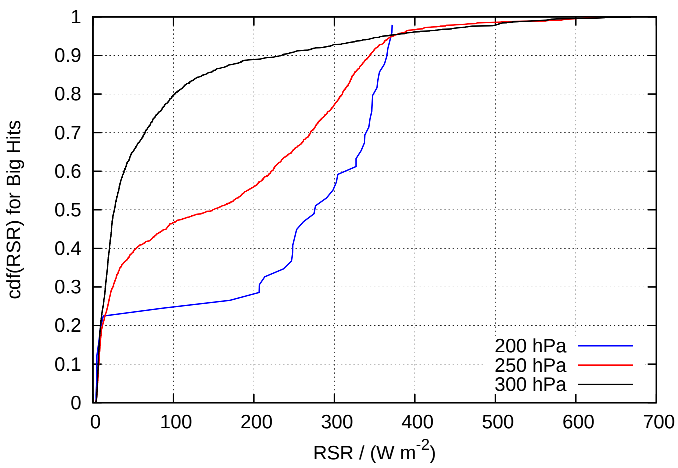


Figure 10: Top: Cumulative distribution of OLR for Big Hits. Overall min and max are 130.7 and 355.3 W m^{-2}. Bottom: the same for RSR, but only including day cases (since RSR= 0 at night). Here, the overall min and max are 0 (night) and 736.1 W m^{-2}.

($\wedge$ is the logical AND). The "background conditions" $SAC = 1$ and $ISS = 1$ are not always written down explicitly in the following.

According to Bayes' law we have

$$P(BH|X = x \pm \Delta x) = \frac{P(X = x \pm \Delta x|BH)\,P(BH)}{P(X = x \pm \Delta x)}.$$

We will not use Bayes' law in this form, but it is interesting to note the prior probabilities $P(BH)$ for the three pressure altitudes. These are: 1% for the 200 hPa level, 7% and 13% for the 250 and 300 hPa levels, respectively. For our application we equate probabilities with relative frequencies and the prior probabilities are simply calculated as

$$P(BH) = N(RF \geq 10\,\mathrm{W\,m^{-2}})/N(SAC = 1 \wedge ISS = 1),$$

where $N(.)$ is the number of all cases (grid points $\times$ time points) where the condition in brackets is fulfilled. In a similar way we can now compute the desired conditional probabilities just by counting:

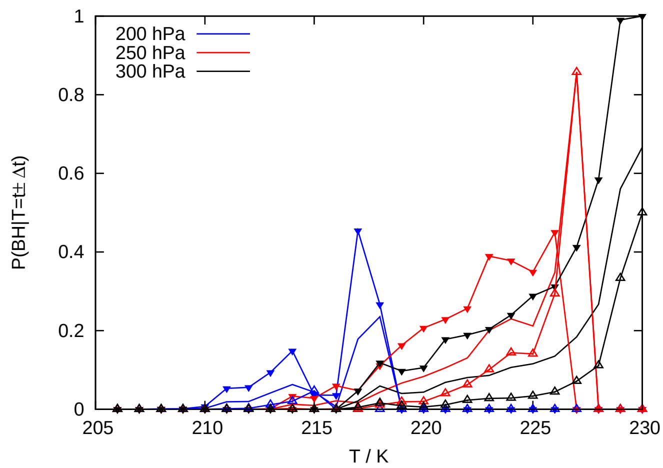


Figure 11: Conditional probability to get a Big Hit conditioned on the value of T in 1 K intervals. Lines without symbols: whole day, filled downward pointing triangles: night cases only, empty upward pointing triangles: daylight cases only.

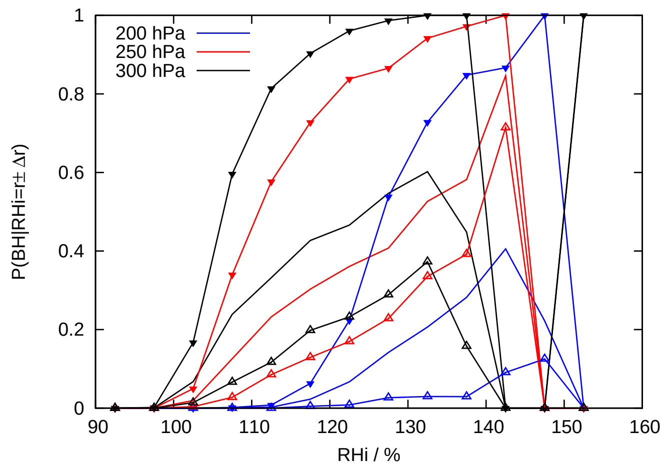


Figure 12: As Fig. 11, but for relative humidity with respect to ice in 5% intervals.

$$P(BH|X = x \pm \Delta x) = \frac{N(X = x \pm \Delta x \wedge RF \geq 10)}{N(X = x \pm \Delta x \wedge SAC = 1 \wedge ISS = 1)}.$$

In the following we show results for the complete day, and for night and daytime only. The latter is an additional condition and is formulated as

$$P(BH|X = x \pm \Delta x \wedge \text{day}, \text{night}) = \frac{N(X = x \pm \Delta x \wedge RF \geq 10 \wedge \mu(><)0)}{N(X = x \pm \Delta x \wedge \mu(><)0) \wedge SAC = 1 \wedge ISS = 1)},$$

where $\mu > 0$ implies daytime, $\mu < 0$ nighttime. Please note that the number of cases is partly low and there is some noise in the figures. I should have plotted error bars, but I didn't in order not to overload the figures.

Figure 11 shows that the probability for Big Hits generally rises with increasing temperature on all pressure levels. As seen above, the probabilities are generally higher for night than for

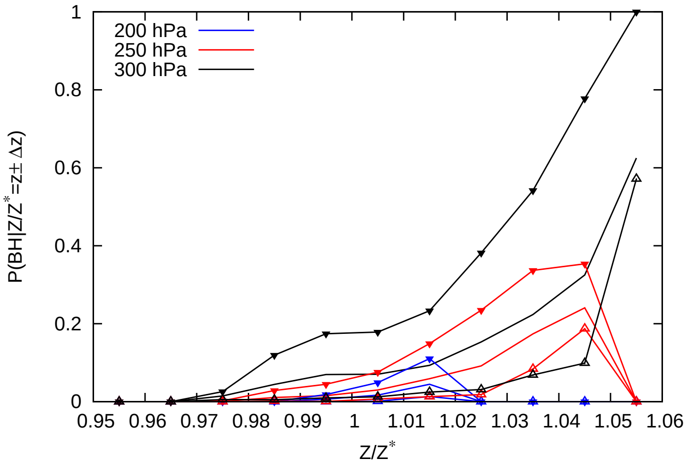


Figure 13: As Fig. 11, but for normalised geopotential height in intervals of 0.01.

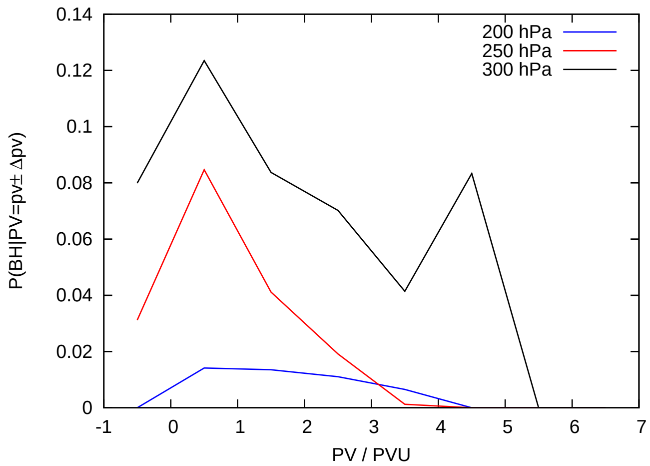


Figure 14: As Fig. 11, but for potential vorticity in intervals of 1 PVU. Only whole day probabilities are shown.

day; accordingly the probabilities are in between these cases for the whole day. The probability gets even 1 at the highest temperatures on the 300 hPa level. I would not give much trust to this result, since the number of cases is very low here (7), and the statistical standard error thus large.

For relative humidity we find, as expected, the probability of Big Hits increasing with the degree of supersaturation, see Fig. 12. The night-curve for 300 hPa displays a wild variation between 140 and 155%, jumping between zero and 1, which again is an artefact of a low number of valid cases.

Next we consider the effect of dynamic conditions on the probability of Big Hits. We begin with a consideration of geopotential height, Z. We note that Z varies on each isobaric level by about 100 dam (dekameter), i.e. 1 km. Obviously, a pressure level is not as level as the expression suggests; it is rather uneven. It is possible to unify the representation for various pressure levels by introducing a standard geopotential height, Z^*_p, defined via a mean tropospheric temperature, $\overline{T} = 255\,\mathrm{K}$, and a corresponding mean pressure scale height, $\overline{H} = R\overline{T}/g = 746\,\mathrm{dam}$. We then

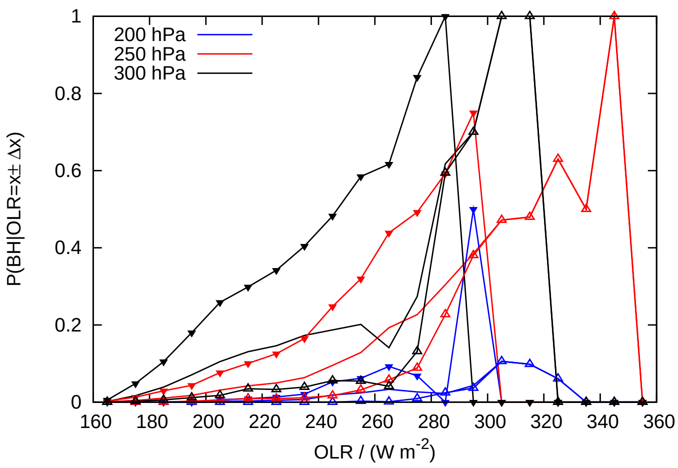


Figure 15: As Fig. 11, but for outgoing longwave raditation (OLR) in intervals of $10\,\mathrm{W\,m^{-2}}$.

define:

$$Z_p^* = \overline{H}\,\ln(1000/p),$$

where p is the pressure in hPa. In this way we get $Z^*_{300} = 898\,\mathrm{dam}$, $Z^*_{250} = 1034\,\mathrm{dam}$, $Z^*_{200} = 1201\,\mathrm{dam}$. Normalisation of Z with the appropriate Z_p^* results in unified ranges of about 0.96 to 1.06 for each level. Figure 13 shows the probability of Big Hits conditioned on the value of Z/Z_p^* for the three levels. We note a tendency of increasing probability with increasing height of the pressure level. It seems that persistent contrails occur predominantly on the tops of the uneven pressure levels and also the Big Hits are most probably found there.

Considering potential vorticity, we find the highest probability for Big Hits at low (tropospheric) PV values, but PV seems to be merely a weak indicator for the occurrence of Big Hits as the conditional probabilities are not much larger than the unconditional probabilities, $P(BH)$. Thus I do not show the night and day curves. Also the presence or not of ambient cirrus seems a weak indicator of the probability of Big Hits (not shown).

The last investigation of this kind concerns the outgoing longwave radiation (OLR) which is basically a measure of the ground and low-level cloud temperature. Figure 13 shows that the probability for a Big Hit increases generally with OLR, a result that is expected since large OLR implies a large temperature contrast between contrail and background and thus a strong longwave forcing. Note that the strong oscillations of the curves at high OLR is again a result of low event counts, that is, insufficient statistics. But the general trend should be a robust result.

Bayesian learning of Big Hit conditions

Now I give an example of combining various conditions to get a relatively robust indication of whether a Big Hit is possible or not. To this end I use the Bayesian law with updating, i.e. in an iterative procedure. I begin with the prior probability of a Big Hit on 250 hPa. From above we know:

$$P(BH) = 0.072.$$

Now we add the condition of night, that is $\mu = -1$:

$$P(BH|\mu = -1) = 0.164,$$

that is, the probability has more than doubled. Next we add the condition of a relative warm situation with $T \geq 225\,\mathrm{K}$:

$$P(BH|\mu = -1 \wedge T \geq 225\,\mathrm{K}) = 0.459,$$

that is, almost half of such cases are Big Hits. Finally we add the condition of a certain degree of supersaturation, $RHi \geq 120\%$ and get:

$$P(BH|\mu = -1 \wedge\, T \geq 225\,\mathrm{K} \wedge\, RHi \geq 120\%) = 1.$$

In my data set these are 17 cases and all are Big Hits.

Note that it does not matter whether all these conditions are applied at once or via updating; in the latter case it does not matter in which order the single conditions are added. These are nice consequences of Bayesian statistics.

Discussion and conclusions

In this document I have shown how we can in principle find and mark conditions for the occurrence of Big Hits. We can do it for a specific situation by application of Schumann's formulas on data from numerical weather prediction. We can do it in a more general way using the statistical results of Bayesian learning and updating as shown above.

The study has demonstrated how it can work in principle, but there are some weak points that can and should be eliminated in near future.

1) We have seen that some of the curves are noisy and the statistical errors are therefore large in some parts of the considered parameter space.

2) I have used all gridpoints and time steps as if they would provide independent results. This is of course completely wrong an assumption. Plots of the RF fields show strong spatial and temporal autocorrelation and this must lead to biased results.

Thus, the study needs a much larger data base in order to get rid of the noise problem and of the autocorrelation problem. For dealing with the latter we must choose a small number of grid points for every time step, chosen at random, so that spatial and temporal autocorrelation is a small as possible.

Another weak point is that we could only compute and consider the instantaneous effects. The real effect is however an accumulation of the instantaneous one over the lifetime and coverage of each contrail. To get this done is a huge and complicated task that requires the lifetime calculation of contrails (including their microphysical evolution, their movement over the sky, the changing ambient conditions). This task could be accomplished with CoCiP, but the results of such a study can probably only be used in a statistical way when running CoCiP operationally for routing purpose is too time consuming. Above I speculated that the lifetime and coverage effect might vary with RF as RF^{a+b}. Perhaps CoCiP can be used to determine these exponents or another form of dependence.

I conclude this study stressing that it seems worth to further investigate Big Hits. They occur in less than about 10% of the cases in the present study, but account for a large share of the total climate effect from contrails. Avoiding Big Hits can thus reduce the contrail contribution to aviations climate impact substantially at relatively low cost. A favourable circumstance in this respect is that most Big Hits occur at night when air traffic is not so dense and where rerouting is easier than during day.

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