TOWARDS DETERMINING THE EFFICACY OF CONTRAIL CIRRUS

M. Ponater[1], M. Bickel[1], L. Bock[1] & U. Burkhardt[1]

[1] Deutsches Zentrum für Luft- und Raumfahrt, Institut für Physik der Atmosphäre, marius.bickel@dlr.de

Abstract. Contrail cirrus has been emphasized as the largest individual component of aircraft climate impact, yet respective assessments are based mainly on conventional radiative forcing calculations. Recent climate model simulations have provided the first estimate of contrail cirrus effective radiative forcing (ERF), which turns out to be much smaller, by about 65%, than its conventional radiative forcing. The reason for the reduction is that natural clouds make up for a considerably lower radiative impact in the presence of contrail cirrus. ERF is generally regarded as a superior metric to indicate the efficacy of some forcing agent to induce surface temperature changes. Hence, the new result may suggest a smaller role of contrail cirrus in the context of aviation climate impact (including proposed mitigation measures) than assumed so far. However, any conclusion in this respect should be drawn carefully as long as no simulations of the global mean surface temperature response to contrail cirrus are available. As a next step, these are needed to confirm the power of ERF for assessing the efficacy of contrail cirrus.

Keywords: Contrail Cirrus, Efficacy, Effective Radiative Forcing, Aviation Climate Impact

INTRODUCTION

Based on a number of radiative forcing (RF) estimates yielded over the last 10 years, contrail cirrus is often supposed to form the largest individual contribution to aviation climate impact (Burkhardt and Kärcher, 2011; Schumann and Graf, 2013; Kärcher, 2018, Bock and Burkhardt, 2019). However, in the last (5th) report of the IPCC it has been recommended to use the effective radiative forcing (ERF) as the most appropriate metric for assessing the quantitative importance of various components of a combined climate forcing. The main reason for this is that the fundamental equation linking radiative forcing to the global mean surface temperature response (ΔT_{sfc}) via the so-called climate sensitivity parameter (λ)

$$\Delta T_{sfc} = \lambda\ RF \qquad (1)$$

is better fulfilled with a constant, forcing-independent λ, if the conventional RF is replaced by the ERF. The discovery that certain forcing agents exhibit a climate sensitivity parameter distinctly different from that of CO_2 (λ^{CO2}) has been accounted for by introducing *efficacy* factors (r), which quantify the specific effectiveness of different forcings to induce surface temperature changes (Hansen *et al.*, 2005).

$$\Delta T_{sfc} = r\ \lambda^{(CO2)}\ RF \qquad (2)$$

Since the climate sensitivity parameter is physically related to the various radiative feedback processes caused by a climate forcing (e.g., Rieger *et al.*, 2017), it can be reasoned that forcings associated with an efficacy factor smaller (larger) than unity induce more negative (positive) feedbacks than the reference forcing, i.e., a CO_2 increase. In previous work, line-shaped contrails have been found to exhibit an efficacy considerably less than unity (Ponater *et al.*, 2005; Rap *et al.*, 2010). Hence, respective investigations targeting the more important contrail cirrus forcing are clearly required. A first attempt to do so, as well as consequences arising from the results, is reported here.

EFFECTIVE RADIATIVE FORCING FROM CONTRAIL CIRRUS

Simulation concept and radiative forcing results

The superiority of ERF as a metric is related to the fact that under this conceptual framework ‘rapid radiative adjustments’, developing on shorter time scales than the slowly responding surface temperature, are included as an integrated part in the radiative forcing value. Hence, a straightforward method to derive ERF is to compare two climate model simulations with fixed sea surface temperature: a sensitivity run including the forcing agent and a reference run omitting it (e.g., Hansen *et al.*, 2005). The ERF is the difference between these two runs of the global and annual mean radiation balance at the top of the atmosphere. Most recently, Bickel *et al.* (2020) presented results applying this method to CO_2 and contrail cirrus forcings, employing a climate model equipped with a state-of-the-art parameterization for contrail cirrus (Bock and Burkhardt, 2016). It is essential to note that Bickel *et al.* (2020) had to scale the contrail cirrus forcing to yield statistically significant results in their climate model simulations. The scaling is required because ERF (its various indisputable merits notwithstanding) has the disadvantage of being associated with a much weaker signal-to-noise ratio than the classical RF. Therefore, the contrail cirrus simulations used as an input flight distances from a 2050 aircraft inventory (Wilkerson *et al.,* 2010), which were multiplied by a factor 12. This yielded a classical RF value of 701 mWm^{-2} and a respective ERF value of 261 mWm^{-2} (see Fig. 1), indicating a reduction of ERF of almost 65%. For optimal comparison with the reference (CO_2) case, a CO_2 forcing of nearly the same classical RF was employed, which resulted in a much smaller ERF reduction of only about 10%. Further simulations reported in Bickel *et al.* (2020, their Fig. 1) confirmed the clearly different relative reductions of ERF, with respect to RF, for the contrail cirrus and the CO_2 forcing.

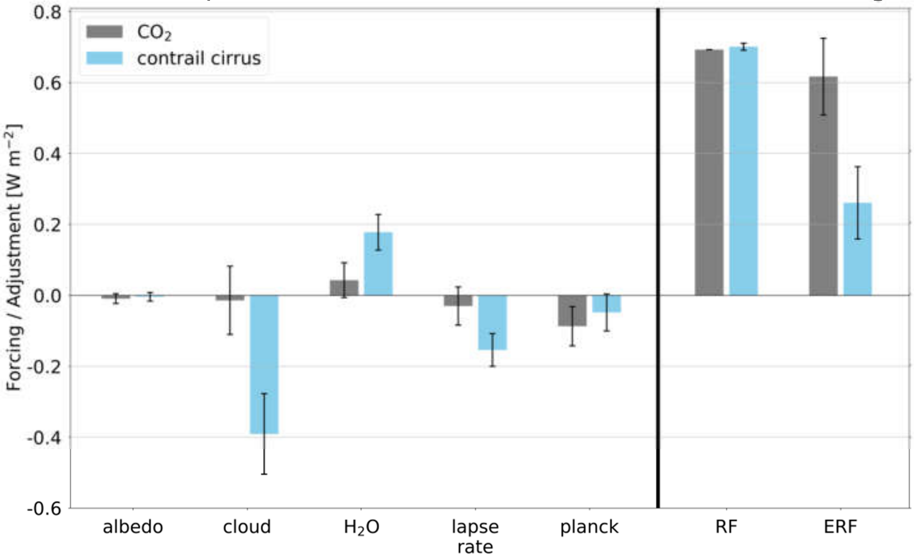

Figure 1. Classical radiative forcing (RF), effective radiative forcing (ERF) and rapid radiative adjustments due to various physical processes (left panel), as yielded by climate model simulations using either contrail cirrus (blue) or CO_2 (grey) as the forcing agent. The forcings in the simulations were scaled (see text) to ensure statistically significant ERF results. Error bars indicate confidence intervals on a 95% significance level.

Analysis of rapid radiative adjustments

As mentioned, the larger reduction of ERF with respect to conventional RF can be traced to its physical origin by means of a complete analysis of feedbacks (Rieger *et al.*, 2017). The result is obvious from the left part of Fig. 1, where the various rapid radiative adjustments contributing to ERF are displayed. The main reason for a stronger reduction auf ERF in the contrail cirrus case is a large negative radiative adjustment from natural clouds. Bickel *et al.* (2020) provide evidence that the (positive, i.e. warming) radiative effect of natural cirrus clouds gets weaker in the contrail cirrus simulation. This can be explained by the physical mechanism that natural and aviation induced cirrus clouds compete with each other, with respect to removing supersaturated water vapor from the ambient atmosphere through condensation to ice particles. Changes of mid-tropospheric clouds may also contribute, but their effect is less statistical significant (Bickel *et al*., 2020, their Fig. 5b). Rapid adjustments in the CO_2 case are generally smaller (mostly statistically insignificant in Fig. 1). Water vapor and lapse-rate adjustment largely compensate each other, as is usual in feedback analysis.

DISCUSSION: CONTRAIL CIRRUS EFFICACY AND CLIMATE IMPACT RELEVANCE

Is the result of the scaled simulations representative for real contrail cirrus?

The conventional RF of contrail cirrus for year 2006 has been determined as 49 mWm^{-2} with reasonable statistical accuracy (Bock and Burkhardt, 2016), but a meaningful value for the respective ERF cannot be simulated directly due to the large statistical uncertainty (Fig. 1). Bickel *et al.* (2020) discuss if the ERF reduction caused by a natural cloud feedback, as derived from scaled inventories, may nevertheless hold for the unscaled case as well. From a series of simulations with gradually increasing scaling factor they conclude that assuming an ERF reduction of similar magnitude for realistic aviation density is tenable. It appears that the underlying physical processes do not depend crucially on the scaling procedure.

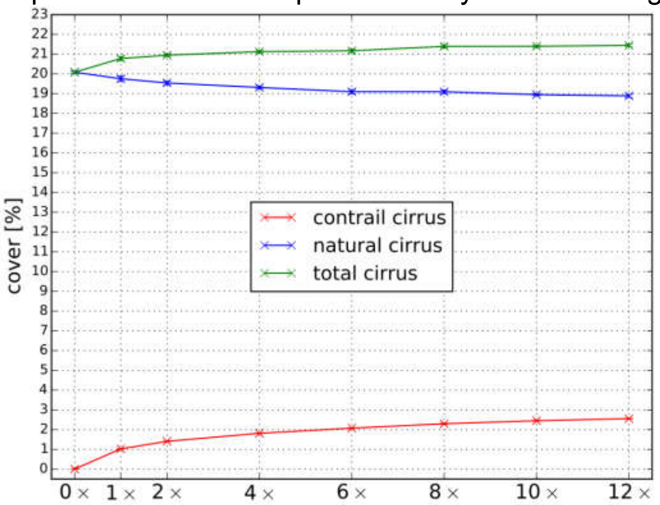

Figure 2. Global mean cover (in %) at 250 hPa for all (green), natural (blue), and aircraft induced (red) cirrus clouds, derived from contrail cirrus simulations using the 2050 aviation inventory with different scaling factors.

For example, cirrus coverage at 250 hPa (Fig. 2) is much less affected by background variability than the radiative impact parameters displayed in Fig. 1. For any scaling factor a substantial decrease of natural clouds in the presence of contrail cirrus is evident, and the effect is also quantitatively similar throughout the simulation series. Hence, the findings for the “scaling factor 12” simulation seem to reflect a consistent process-related interaction.

Is the ERF/RF ratio a reliable substitute for contrail cirrus efficacy?

The conclusion that contrail cirrus ERF is only 35% of the respective classical RF does not automatically imply that the contrail cirrus efficacy will be 0.35 . Rather, by formulating Eq. (2) for contrail cirrus (indicated by “cc”) and CO_2 in both the classical and the ERF framework

$$\Delta T^{(CO2)}_{sfc} = \lambda^{(CO2)} RF^{(CO2)} = \lambda'^{(CO2)} ERF^{(CO2)} \quad (3a)$$

$$\Delta T^{(cc)}_{sfc} = r^{(cc)} \lambda^{(CO2)} RF^{(cc)} = r'^{(cc)} \lambda'^{(CO2)} ERF^{(cc)} \quad (3b)$$

it is easily realized that

$$ERF^{(cc)}/RF^{(cc)} = r^{(cc)} \left(ERF^{(CO2)}/RF^{(CO2)}\right) / r'^{(cc)} \quad (4)$$

Hence, the classical contrail cirrus efficacy, $r^{(cc)}$, only equals $ERF^{(cc)}/RF^{(cc)}$, if $ERF^{(CO2)}$ and $RF^{(CO2)}$ are identical *and* if the contrail cirrus efficacy in the ERF framework is unity. The first condition is usually fulfilled within a 10% range (see Fig. 1, or Richardson *et al.*, 2019). The second condition, as mentioned above, is the basic expectation and motivation when using the ERF framework, but examples to the contrary have also been demonstrated (e.g., Marvel *et al.*, 2016). Therefore we state that contrail cirrus efficacy is insufficiently known at the present stage. Direct simulations of the surface temperature response and climate sensitivity, using a coupled atmosphere/ocean model, are necessary for this purpose.

Can contrail cirrus still be regarded as a most relevant part of aviation climate impact?

If the ERF/RF factors reported here are used to convert published estimates of realistic aviation RF to ERF (and if model, parameter, and statistical uncertainties are left aside), it might be argued that contrail cirrus can no longer be regarded as the most important aviation climate impact component (Fig. 3). We think, however, that this would be a superficial and premature conclusion. First, Bickel et al. (2020) point out that contrail cirrus ERF results from only one climate model need independent backing from other models, particularly because cirrus cloud feedbacks (of crucial importance here) have shown large inter-model spread even for the CO_2 case. Second, as mentioned above, the actual efficacy of contrail cirrus is still to be determined by direct simulations. This will be the next step using our climate model.

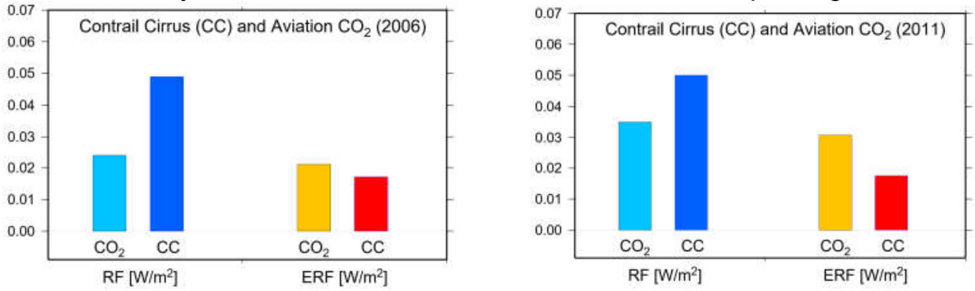

Figure 3. Classical RF from contrail cirrus and CO_2 (dark and light blue, respectively) for realistic aviation scenarios: Values adopted from Kärcher (2018, right) and from Bock and Burkhardt (2019, left). The ERF (red) counterparts have been yielded by using the ERF/RF reduction factors as derived by Bickel *et al*. (2020). Uncertainty bars are deliberately omitted.

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