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Can we reliably assess climate mitigation options for air traffic scenarios despite large uncertainties in atmospheric processes?

K. Dahlmann [a,*], V. Grewe [a,b], C. Frömming [a], U. Burkhardt [a]

[a] Deutsches Zentrum für Luft- und Raumfahrt, Institut für Physik der Atmosphäre, Oberpfaffenhofen, Germany
[b] Delft University of Technology, Faculty of Aerospace Engineering, Section Aircraft Noise & Climate Effects, Netherlands

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ABSTRACT

Air traffic has an increasing influence on climate; therefore identifying mitigation options to reduce the climate impact of aviation becomes more and more important. Aviation influences climate through several climate agents, which show different dependencies on the magnitude and location of emission and the spatial and temporal impacts. Even counteracting effects can occur. Therefore, it is important to analyse all effects with high accuracy to identify mitigation potentials. However, the uncertainties in calculating the climate impact of aviation are partly large (up to a factor of about 2). In this study, we present a methodology, based on a Monte Carlo simulation of an updated non-linear climate-chemistry response model AirClim, to integrate above mentioned uncertainties in the climate assessment of mitigation options. Since mitigation options often represent small changes in emissions, we concentrate on a more generalised approach and use exemplarily different normalised global air traffic inventories to test the methodology. These inventories are identical in total emissions but differ in the spatial emission distribution. We show that using the Monte Carlo simulation and analysing relative differences between scenarios lead to a reliable assessment of mitigation potentials. In a use case we show that the presented methodology can be used to analyse even small differences between scenarios with mean flight altitude variations.

1. Introduction

Climate change and its consequences are more and more of public concern, especially since the last report of the Intergovernmental Panel on Climate Change (IPCC, 2013). It is extremely likely that more than half of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in greenhouse gas concentrations and other anthropogenic forcings (IPCC, 2013).

The climate impact of current air traffic contributes 4.9% with a range of 2–14% to global warming in terms of radiative forcing (Lee et al., 2009) and air traffic is expected to grow further by about 5% per year (ICAO, 2013). Thus, it is more and more important to reduce the climate impact of aviation. For mitigation measures, it is not sufficient to analyse CO_2 emissions only, as non-CO_2 effects play a crucial role (IPCC, 1999; Lee et al., 2009). The most important non-CO_2 effects are water vapour emission (IPCC, 1999), formation of line-shaped contrails (Schumann, 1996) and contrail cirrus (Burkhardt and Kärcher, 2011), as well as NO_x emissions ($NO_x = NO + NO_2$) which lead to changes in ozone and methane concentrations

* Corresponding author.
E-mail address: Katrin.Dahlmann@dlr.de (K. Dahlmann).

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(e.g. Grooß et al., 1998). These non-CO_2 effects are particularly important for the climate impact of air traffic as their impact depends on the location of the emission. This refers to contrail formation and chemistry effects, such as the formation of ozone (Schumann, 2000; Grewe et al., 2002a; Grewe and Stenke, 2008; Rädel and Shine, 2008; Köhler et al., 2008; Frömming et al., 2012; Köhler et al., 2013; Williams et al., 2014), and the radiative response to a local perturbation (Lacis et al., 1990; Stuber et al., 2005). Dahlmann et al. (2011), for example, show that the ozone production efficiency of air traffic NO_x emissions is twice as large as that of surface emissions, e.g. by road traffic. In addition, the climate impact from air traffic-induced ozone change is larger than that of an ozone change at the Earth's surface, because the radiative impact of a greenhouse gas increases with increasing temperature difference between the surface and the atmospheric layer into which it is emitted (Lacis et al., 1990). The formation of contrails also depends strongly on the location of the emission, since persistent contrails only form in ice supersaturated regions, which occur mainly near the tropopause (Sausen et al., 1998). The impact of contrails depends on the altitude and latitude of the emission location, as the altitude of the tropopause and the available water for deposition depends on the latitude (Newinger and Burkhardt, 2012). Due to the dependency of the climate impact on altitude and latitude of different emissions, there is no general linear relationship between fuel consumption and climate impact. Therefore, mitigation options can lead to counteracting effects. On the one hand, a general reduction in flight altitude, for example, leads to a reduced climate impact from ozone, water vapour, and contrail formation (Frömming et al., 2012). On the other hand, a reduction in flight altitude leads to increased fuel consumption and thus to an increased climate impact from CO_2 (Frömming et al., 2012). Hence, it is important to simultaneously include all relevant climate agents when assessing the climate impact of mitigation scenarios.

The analysis of the climate impact of aviation, from the emission to changes in atmospheric concentrations, changes in radiation and temperatures, and consequently the decision which mitigation option has the highest reduction potential is complicated because of large uncertainties in the calculation of the atmospheric changes due to aviation emissions (Lee et al., 2009). A large part of the uncertainties arises from a spread of model results due to different calculation methods (e.g. different chemistry or cloud schemes). To ensure a reliable assessment of mitigation options, it is necessary to base it on statistically significant results, and therefore it is important to include uncertainty considerations.

The objective of this paper is to introduce a methodology that enables a reliable assessment of mitigation potentials for different emission scenarios despite large uncertainties in the overall climate impact of aviation. We introduce the methodology and present the principle mechanism with an example, which shows that although considerable uncertainties in the overall climate impact from air traffic exist, a reliable assessment of mitigation options can be achieved. Finally, a use case is presented, which assesses general flight altitude changes.

2. Method

2.1. AirClim – an efficient assessment tool

The climate impact of air traffic emissions is usually calculated in detail by using a complex three dimensional climate chemistry model, which considers all relevant atmospheric processes (e.g. Grewe et al., 2002b; Köhler et al., 2008; Hoor et al., 2009). As these simulations are computationally very expensive, it is not possible to use them for uncertainty assessments within Monte Carlo simulations, where the uncertainty is analysed by a large number of random experiments. Instead, we use the climate response model AirClim (Grewe and Stenke, 2008) in this study. AirClim combines precalculated atmospheric impact data with air traffic emission data to calculate e.g. aviation climate impact for a multitude of emission inventories. For the precalculated data, idealised emission regions with normalised emission strength are defined. For each of the idealised emission regions, a climate-chemistry simulation is performed, employing normalised emissions of nitrogen oxides and water vapour to obtain the chemical response, i.e. the simultaneous effect of nitrogen oxides and water vapour. Chemical perturbations and radiative forcing of ozone (O_3), methane (CH_4), water vapour (H_2O), and contrails are calculated with a state-of-the-art climate-chemistry model (E39/CA, e.g. Stenke et al. (2008)). For contrail cirrus we have used ECHAM4-CCMod (Burkhardt and Kärcher, 2009). The results of these detailed simulations constitute the precalculated atmospheric input data for AirClim. AirClim combines the precalculated, altitude and latitude dependent perturbations with emission data in order to calculate composition changes, radiative forcing and near surface temperature changes caused by these emissions. Near surface temperature change is presumed to be a reasonable indicator for climate change (Grewe and Stenke, 2008). AirClim is applicable to evaluate numerous air traffic scenarios, including different routings and technological options.

The benefit of this methodology is that the time expensive precalculations only have to be done once, and can then later be used for any AirClim simulation. A detailed description and validation is given in Grewe and Stenke (2008). Here we apply an extended AirClim version with a higher resolution, especially at mid latitudes and cruise altitudes (Fichter, 2009), and additional consideration of the climate impact of long-lived ozone reduction (O_3^{pm}) and contrail cirrus (Contrail induces cloudiness, CiC) (Appendix; Dahlmann, 2012; Grewe and Dahlmann, 2012).

2.2. Uncertainty assessment with Monte Carlo simulation

In calculating the climate impact of aviation large uncertainties exist. To ensure that the chosen mitigation option will lead to a reduction in climate impact, we consider these uncertainties in a meaningful way. In AirClim we assume