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Publication date
2020

Document Version
Final published version

Citation (APA)
Dahlmann, K., Matthes, S., Yamashita, H., Unterstrasser, S., Grewe, V., & Marks, T. (2020). *Assessing the climate impact of formation flights*. 171-175. Abstract from 3rd ECATS conference.

ASSESSING THE CLIMATE IMPACT OF FORMATION FLIGHTS

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Abstract. An operational measure to aim for mitigation of aviation climate impact that is inspired by migrant birds is to fly in aerodynamic formation. This operational measure adapted to human aircraft would eventually save fuel and is, therefore, expected to reduce the climate impact of aviation. As this method changes beside the total emission also the location of emission it is necessary to assess its climate impact with a climate response model to assure a benefit for climate. Therefore, the climate response model AirClim was adopted to account for saturation effects occurring for formation flight. The results for case studies comprising typical air traffic scenario show that on average the fuel consumption can be decreased by 5%, the climate impact, however, can be reduced by up to 24%.

Keywords: climate impact, formation flight, mitigation potential, aircraft wake-surfing for efficiency

INTRODUCTION

Aviation aims to reduce its climate impact. Hence, quantitative estimates of potential reduction in climate change from individual mitigation strategies are required, in order to identify promising mitigation options. Operational measures offer mitigation potentials that are accessible without adapting the aircraft structure, aerodynamics or engine technology, and might be available within shorter time scales. Such an operational mitigation strategy is inspired by migrant birds that fly in formation to save energy. This method can be adopted by aircraft and lead to substantial fuel savings as the thrust of the trailing aircraft, which is literally surfing on the vortex of the leading aircraft, can be reduced during cruise flight. This procedure can likewise be called aircraft wake-surfing for efficiency (AWSE). This in turn changes the climate effect of aviation as the amount and the location of the emissions change due to the formation flight and the AWSE benefits. This effect is even enlarged, as saturation effects occurring behind the formation can lead to an additional benefit in terms of climate impact.

METHOD

The nonlinear climate response model AirClim (Grewe and Stenke, 2008; Dahlmann *et al.*, 2016) is used to calculate the change in climate impact due to formation flight. AirClim comprises a linearization of atmospheric processes to establish a direct link between emission and near surface temperature change, which is presumed to be a reasonable indicator for climate change. AirClim has been designed to be applicable to climate assessment of different aircraft technologies and operations. It includes the climate impacts of the climate agents CO_2, H_2O, CH_4 and O_3 (latter two resulting from NO_x-emissions) and contrail cirrus (CiC). The climate response model combines a number of previously calculated atmospheric data with aircraft emission data to obtain the temporal evolution of atmospheric concentration changes, radiative forcing and temperature changes.

For formation flights of two aircraft the trailing aircraft (follower) maintains a position in the vortex of the leading aircraft (leader). The close proximity of the aircraft leads to the creation of only one contrail, which incorporates different geometrical, microphysical and optical properties compared to a contrail created by a single aircraft (Unterstrasser and Stephan, 2020). Dedicated Large Eddy Simulations (LES) of the contrail-cirrus evolution showed that in formation flight scenarios the total ice mass, which is used as a proxy for changes in the longwave radiation, is reduced by 20-50%, while the total extinction (proxy for shortwave radiation changes) is reduced by 30-60% (Unterstrasser, 2020). The reduction in longwave forcing reduces the warming effect of contrails, while the reduction of shortwave forcing reduces the cooling effect from contrails. The net effect depends on the ratio between longwave and shortwave forcing. As the contrail cirrus parametrisation in AirClim is based on simulations from Burkhardt and Kärcher (2011), we used the longwave-shortwave ratio from these simulations. In total this leads to a mean net reduction of radiative forcing of 48% in our simulations.

In addition to the saturation effects from contrail, saturation effects for NO_x can occur during formation of aviation-induced ozone. The ozone chemistry is highly nonlinear, which can lead to saturation effects if instead of two aircraft flying separately the two aircraft fly in formation and emit in the identical air mass. Therefore, climate model simulations with EMAC were performed in order to study non-linearities within the North Atlantic Flight corridor (NAFC), studying an emission between 50% and 100% of NO_x emissions. The results on aviation-induced ozone formation show that if NO_x is emitted in the identical air mass, ozone production efficiency decreases by 5%, which causes a lower overall efficiency of emitted NO_x emissions, hence leading to a weaker associated climate effect.

The climate response model AirClim was adapted to account for these saturation effects occurring while flying in formation. Therefore AirClim decreases the CiC and ozone impact by 48 and 5%, respectively when the aircraft fly in formation. Thereby the mitigation benefit is split evenly between leader and follower. The climate impact is calculated as an average global near surface temperature (Average temperature response, ATR) over a time horizon of 50 and 100 years:

$$A\text{TR}100 = \int_0^{100} \Delta T(t)dt \tag{1}$$

Calculation of the climate impact with the climate response tool AirClim requires emission data as input for individual model simulations. AirClim analyses the mitigation potential by comparing the climate impact of two distinct emission inventories for a given set of city pairs, a reference case which represents aircraft routing in a conventional way (fuel optimal) and a formation case which assumes aircraft to fly in formation with AWSE benefits whenever it is favorable under fuel optimal conditions. Individual traffic samples used in this study as input for AirClim are described in more detail in the next section.

EMISSION INVENTORIES: CASE STUDIES OF AIRCRAFT ROUTES

In this paper we use four set of city-pairs that were identified to have a potential for formation flight between most active airports in the world. A detailed description on the construction of the emission inventories is provided in Marks *et al.*, (2020). They analyzed a global study involving all airports leading to a set of 555 flights (All). In a similar way the 50 most popular airports (TOP50) and the 30 most popular airports (TOP30) were analyzed in order to identify city pair connections with a potential for formation flight. Additionally we used emission inventories of a North Atlantic study (NAT) with a special focus on the influence of wind on the formation.

RESULTS

In order to provide a quantitative estimate of the formation flight mitigation potential, this paper presents differences in the climate impact between the formation flight case and a reference case for four distinct scenarios. Relative changes in climate impact, indicated as average temperature response (ATR100) for the leading and following aircraft as well as for the total formation for the TOP50 scenario are presented in Figure 1 (left). The total climate impact mitigation potential for the formation is about 23%, while the climate impact of the leading aircraft (leader) is reduced by 15% and the climate impact of the following aircraft (follower) is reduced by 31%. Specifically, AWSE increases the fuel consumption and NO_x emissions of the leader, but leads to reduced fuel consumption and NO_x emissions of the follower (Figure 1 right). For the total formation (both aircraft together) fuel consumption as well as NO_x emissions decreases by 5% and 10%, respectively. The total flown distance increases as both aircraft have to fly detours to the rendezvous points (geographic location where aircraft are scheduled to meet the other aircraft in order to start formation flight with AWSE).

Changes in total climate impact originate from individual effects of aircraft emissions, comprising CO_2 and non-CO_2 effect. Detailed analysis of individual effects can provide information which effects dominate the mitigation potential. The main contributor to the reduced climate impact is the reduced impact of contrail cirrus (CiC) due to the saturation effects described above. This shows a mitigation potential associated with a reduced contrail cirrus effect of about 15%. Additionally 7% reduction can be attributed due to reduced NO_x emissions, while the impact of CO_2 due to reduced fuel consumption amount to only about 1%. Summing up these relative contributions results in an overall mitigation potential of 23% of the total formation (Total).

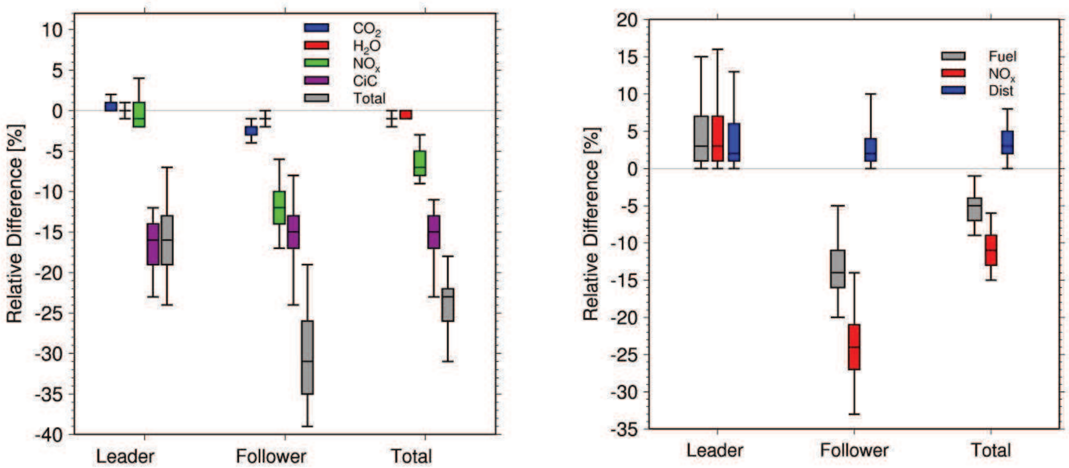

Figure 1 Relative change in climate impact of the different species (left) and fuel consumption, NO_x emissions and flown distances (right) for leader, follower and the Total formation and the Top50 scenario.

Comparing individual impacts between leader and follower shows that while contrail effects are estimated to be reduced by about the same amount for both aircraft, this is not the case for CO_2 and NO_x. Here stronger differences of attributable reductions between leader and follower become apparent. Change of climate impact of CO_2 amounts to +1% versus -2%, comparing leader to follower. This difference can be directly attributed to the changed emissions, as the impact is directly proportional to emitted amounts. For the NO_x impact we find reductions of -1% and -12% comparing leader to follower. This difference is partly attributed to changed emissions, which then have a different impact, as non-linear photochemical processes drive ozone formation in the atmosphere.

Beside the TOP50 scenario, three additional cases were analyzed: All, Top30 and NAT. Comparing the total mitigation potential of these case studies shows only a small variation of the median of the estimated mitigation potential between 23 and 24% (Figure 2 left). Nevertheless the total impact of the individual formations in the traffic sample provides a spread between 13 and 33%. Only the NAT study shows reduced spread from 13 to 27% reduction. The fuel consumption and NO_x emissions for the formation flights of the global study are reduced by about 6% and 12%, respectively (Figure 2 right). In contrast the flown distances are increased by about 3%. For the NAT study the fuel consumption and NO_x emissions are reduced by 7% and 13%, respectively, while the flown distance is increased by only 1%.

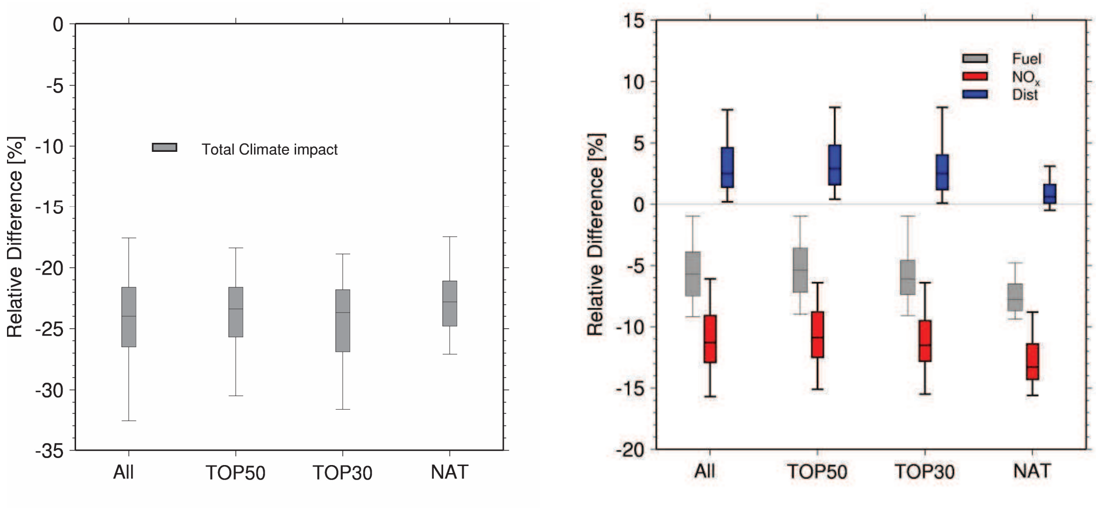

Figure 2: Overview of the total climate impact mitigation potential (left) and the change in fuel consumption, NOx emission and flown distances (right) for the analyzed studies.

CONCLUSION

Several case studies indicate that the climate impact of aviation could be reduced by one quarter by introducing formation flight procedure with AWSE benefits. While one part of this reduction potential can be attributed to reduced emissions, 5% in CO_2 and 10% in NO_x, a second part can be attributed to changes in the atmospheric processes involved, during contrail processes and formation of aviation–induced ozone in the atmosphere. Due to formation flight the flown distance increases by 1-3%. This is more than only the effect due to the reduced emissions would suggest.

This mitigation potential is achievable for those formations that have a potential for formation flight and which currently (using available flight plans) represent only a small fraction of global flights according to Marks *et al.* (2020). An optimization of the flight plans in favor of the creation of AWSE formations would eventually raise the full climate mitigation potential.

ACKNOWLEDGEMENTS

This work has received funding from the German Ministry of Economic Affairs and Energy (BMWi) under the National Aeronautical Research Programme (LuFo) V-2 under the grant agreement no. 20E1508C.

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