THE EXPECTED IMPACT FROM THE INTRODUCTION OF A NEW STRUT-BRACED WING AIRCRAFT CONFIGURATION ON GLOBAL AIR TRAFFIC EMISSIONS AND CLIMATE – RESULTS FROM THE WECARE PROJECT

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Abstract. Aviation is expected to contribute significantly to the anthropogenic climate change and hence climate impact reduction measures are required as soon as possible. Therefore, the DLR project WeCare deals with the investigation of potential strategic and tactical options for the reduction of aviation's climate impact. Here, we present the results of an analysis of the global emission distribution and a climate impact assessment for the introduction of a Strut-Braced Wing (SBW) aircraft into the air transportation system, which was carried out within WeCare. A model chain consisting of an air traffic demand and aircraft movement forecasting model, an aircraft fleet aging and renewal simulation, an advanced methodology to generate air traffic emission inventories and a climate impact assessment tool has been applied to study how new aircraft configurations might contribute to a reduction of aviation's climate impact in the future. We found that the SBW aircraft has the potential to reduce fuel consumption of the aircraft fleet of the seat category 100-150 seats by nearly 26% in 2050 due to its reduced drag and a higher propulsion efficiency of the Counter-Rotating Open Rotor (CROR) engine it is equipped with. NO_x emissions can even be reduced further by 45% due to a new lean combustion technology. The climate impact assessment indicates that this large reduction potential – in combination with a slightly lower cruise altitude of the SBW aircraft compared to today's reference aircraft – may reduce the warming caused by aircraft of that size (including the projected growth in the future) by nearly 17%.

Keywords: strut-braced wing, new aircraft configuration, technological measures, environmental impact, global air traffic emissions, emission inventory, climate impact

INTRODUCTION

Air travel is a key part of our society and the gradual increase in air traffic demand is expected to result in a multiplication of aircraft movements in the coming decades (AIRBUS, 2014). Emissions from aircraft engines on the other hand cause significant changes of concentrations of radiative forcing agents at usual cruising altitudes, making aviation's climate impact an exceptional challenge which is subject of various research activities (Lee et al., 2010). One of these projects, called WeCare (Utilizing Weather information for Climate efficient and eco efficient future aviation) is currently being carried out internally by the German Aerospace Center. Based on previous findings (e.g. Koch, 2013) the project aims at evaluating different ways how the climate impact of aviation can be mitigated both strategically, e.g. through the introduction of new aircraft types or systematic changes of flight operations, and tactically, e.g. by using daily-based meteorology to circumnavigate certain "climate-sensitive" regions (Niklaß et al., 2014). For instance, recently the project team analysed to what extent the introduction of stopovers during long-haul flights could contribute to a reduction in fuel consumption and global emissions as well as to a change of the corresponding climate impact. For this purpose, a modelling system has been developed that is capable of simulating global air traffic scenarios and performing respective emission and climate impact assessments based on the introduction of such new operational concepts (Linke et al., 2016). This simulation environment also includes models that allow for a projection of regionally distinguished air travel demand (Terekhov et al., 2015) and a derivation of expected future flight movements on a route and aircraft category basis (Ghosh et al., 2015). On the technological side, the project is investigating a new aircraft configuration known as Strut-Braced Wing aircraft (SBW). The aircraft itself is designed in a different DLR project, but preliminary design characteristics have already been provided by the design team. SBW aircraft are characterized by supporting struts connecting the wings to the fuselage and reduce wing loads accordingly. Such a design which is actually widely used for General Aviation aircraft, like e.g. Cessna 172, allows for the construction of thinner wings and thus – assuming a constant wing mass – an increase of the wing span and aspect ratio. The latter goes along with a higher aerodynamic efficiency due to the reduced induced drag which in turn leads to a reduced weight compared to a conventional cantilever wing design. In combination, this allows for the use of smaller engines with reduced fuel consumption and less emissions while providing a similar transport capacity as a conventional narrow-body aircraft (Sanchez Barreda, 2013). The purpose of this study is to apply the above mentioned methodology to assess the expected impact resulting from the introduction of the SBW aircraft configuration on global air traffic emissions and climate. In the following section, the methodology is described before preliminary results are presented in section 3. Section 4 completes the paper with conclusions and an outlook.

METHODOLOGY AND APPLICATION

Here, we assess the SBW aircraft with respect to its environmental impact. The focus is laid on the global distribution of gaseous emissions as well as on the corresponding changes of the Average Temperature Response over a period of 100 years (ATR100), which has been proven to be an adequate climate metric for such assessments (Grewe and Dahlmann, 2015). Due to the global character of the study, local effects at airports, such as implications on noise and local air quality issues are not considered here.

For the assessment, a modeling suite is used which is described below; furthermore, simulating the insertion of a complete new aircraft type into the air transportation system requires certain assumptions concerning the future air traffic network, which it is introduced into, depending on the envisaged Entry-Into-Service (EIS). As the environmental impact mainly depends on the aircraft characteristics in terms of aircraft and engine performance, also some details of the SBW design are outlined below.

MODELING SYSTEM

For the study presented here, DLR's *Global Air Traffic Emissions Distribution Laboratory* (GRIDLAB) was applied. GRIDLAB combines modules for the calculation of flight missions based on aircraft performance data with flight planning and optimization capabilities as well as with emission models to compute emission distributions along aircraft trajectories. Thus, not only changes of cumulated amounts of gaseous emission provoked by new technologies or altered flight operations can be captured, but also their variation in altitude and geographic location. Details of the modelling system can be found in (Linke, 2016). The inputs to the model chain constitute air traffic scenarios that have been derived using an air travel demand and flight movement forecasting system (AIRCAST; Terekhov et al., 2015; Ghosh et al., 2015; Kölker et al., 2016). Based on these scenarios and further assumptions regarding the introduction of new technological or operational measures, like e.g. the introduction of a SBW aircraft, GRIDLAB produces emission inventories which are eventually transferred into the climate impact assessment tool AirClim developed by DLR (Grewe and Stenke, 2008). In order to increase computational efficiency, the modelling system makes use of a database of precalculated 'reduced' emission profiles that has been generated by a detailed trajectory and emission calculation for the respective SBW aircraft (see technical specifications below) as well as the reference aircraft which is used to model the business-as-usual scenario. For simulating the flight missions it is generally assumed that the aircraft tends to fly as close as possible to its respective optimum altitude (i.e. the altitude in which the aircraft is most fuel efficient).

ASSUMED AIR TRAFFIC SCENARIO

For the ecological assessment of the introduction of a SBW aircraft configuration, assumptions regarding its EIS as well as the duration of the introduction phase ("ramp-up") have to be made. Here, we assume that the SBW is supposed to substitute an existing aircraft category of 100-150 seats (e.g. Airbus A320, Boeing 737) and that introduction starts in 2015. Using AIRCAST, aircraft movements of the respective aircraft category are projected into the future from 2015 to 2050, resulting in datasets containing departure and destination cities as well as annual flight frequencies for the connections using a time step of 5 years. Baseline for the development of regional demand properties are economic parameters obtained from the so-called *Randers* scenario (Randers, 2012). Previous studies have shown that the seat category 100-150 seats contributes to about 18-19% of the Available Seat Kilometres offered by the global world fleet; for the sake of simplicity an Airbus A320 aircraft performance model obtained from EUROCONTROL's Base of Aircraft Data (BADA, Version 4.1; Mouillet, 2013) is used to model all flights of that seat category as it is the most frequently operated aircraft type in that category. In this "business-as-usual" scenario we assume, that today's technology levels will be maintained throughout the projection until 2050. In contrast, in the SBW scenario we substitute the A320 class gradually by the SBW aircraft according to a substitution plan calculated with DLR's Fast Forward FFWD (Apffelstaedt et al., 2008) module that models aircraft fleet aging, disposal and renewal.

SBW AIRCRAFT AND ENGINE CHARACTERISTICS

The SBW aircraft design is conducted within the DLR project FrEACs; preliminary design data, including aircraft performance data is provided for this study. The main aircraft characteristics are listed in Fig.1, which also shows a visual impression of the current design state. The aircraft is equipped with a Counter-Rotating Open Rotor (CROR) engine, which is one of the new engine concepts currently under investigation by engine and propulsion scientists. The CROR engine provides a high propulsion efficiency due to a large rotor diameter and respective ultra-high bypass ratios without losing specific thrust due to additional weight and drag caused by large nacelles as with turbofan engines of a similar size (Plohr, 2015). The CROR engine designed by DLR (DLR-CROR) is assumed to contain a so called Twin Annular Premixing Swirler (TAPS) as first used in the GEnx engine. It applies a two-stage lean combustion technique that allows for a significant reduction of NO$_x$ emissions under cruise conditions. Due to a completely different combustion behavior compared to conventional engines usual fuel flow correlation methods for the determination of emission indices (EI) are not applicable here. Instead, an EI estimation is used which is based on a thermodynamic process model developed by DLR for the GEnx-1B70 as the CROR is expected to have similar process characteristics.

Design range	2000 NM
Maximum take-off weight	73.2 t
Maximum payload	18.6 t
Maximum fuel capacity	9.8 t
Reference wing area	110 m²
Pax seats (up to)	154
Cruise Mach number	0.72
Take-off field length	1970 m
Engine	DLR-CROR
Thrust	111.2 kN

Figure 1. Strut-Braced Wing aircraft design and main characteristics

One of the key challenges in integrating the TAPS into a CROR engine with a significantly smaller mass flow and thus a smaller combustor size is the miniaturization. Here, we assume that in the future a downscaling of the TAPS combustor will be possible while maintaining the same emission level as with the GEnx TAPS today. Based on that assumption, the SBW-CROR emission behavior is modeled by applying the EIs of the GEnx-1B70 obtained from the ICAO engine emission databank for take-off, climb and approach phases. For cruise an average EI simulated with the above mentioned GEnx model for the same mission conditions is used (Plohr, 2016). It should be noted that the combination of the aerodynamic advantages of a Strut-Braced Wing with the CROR engine technology (higher propulsion efficiency) and the TAPS combustor concept leads to a significant reduction of fuel consumption as well as NO$_x$ emissions compared to the technology levels used in today's aircraft.

RESULTS

In order to estimate the climate impact from the introduction of a SBW aircraft into the global air transportation system, first emission inventories were calculated for both, the business-as-usual scenario and the SBW scenario, for the years 2015 to 2050. The relative share of the SBW fleet from the entire aircraft fleet under consideration is depicted in Fig. 2.

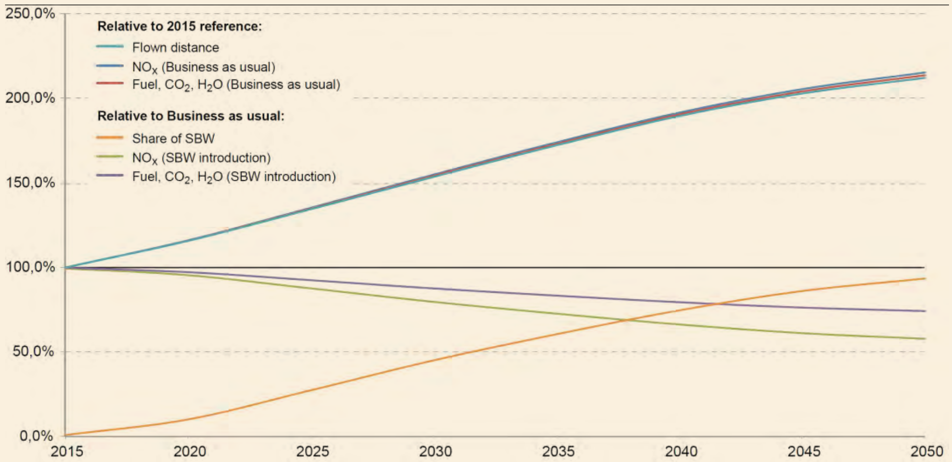

Figure 2. Relative development of fuel consumption and emissions in the scenarios

It can be seen that – according to this substitution plan – there is a 50% share reached in 2032, whereas in 2050 the share amounts to 93%. Over the entire period the flown distance more than duplicates. The fuel consumption and the overall NO_x emission amount in the business-as-usual scenario increases by approximately 110% compared to the 2015 level. With the SBW introduction, the fuel consumption can be decreased by nearly 26% by the year 2050 relative to the reference scenario (today's technology level). Due to the special low-NO_x CROR engine the NO_x emission level can even be reduced by 45% in 2050. The fuel consumption reduction that can be achieved through the introduction of a SBW aircraft is shown in the differential inventory in Fig. 3. From the figure, the global route structure, which aircraft of the seat category 100-150 seats will be operated on in the future, is obvious. Regions of dark red color mark areas where the SBW aircraft introduction would lead to large fuel savings. The more flights are operated on those routes, the more fuel can be saved through the utilization of an SBW aircraft instead of a conventional short-haul aircraft. Especially the Chinese airspace is characterized by large potential savings as in 2050 there is a huge amount of air traffic projected in the respective seat category.

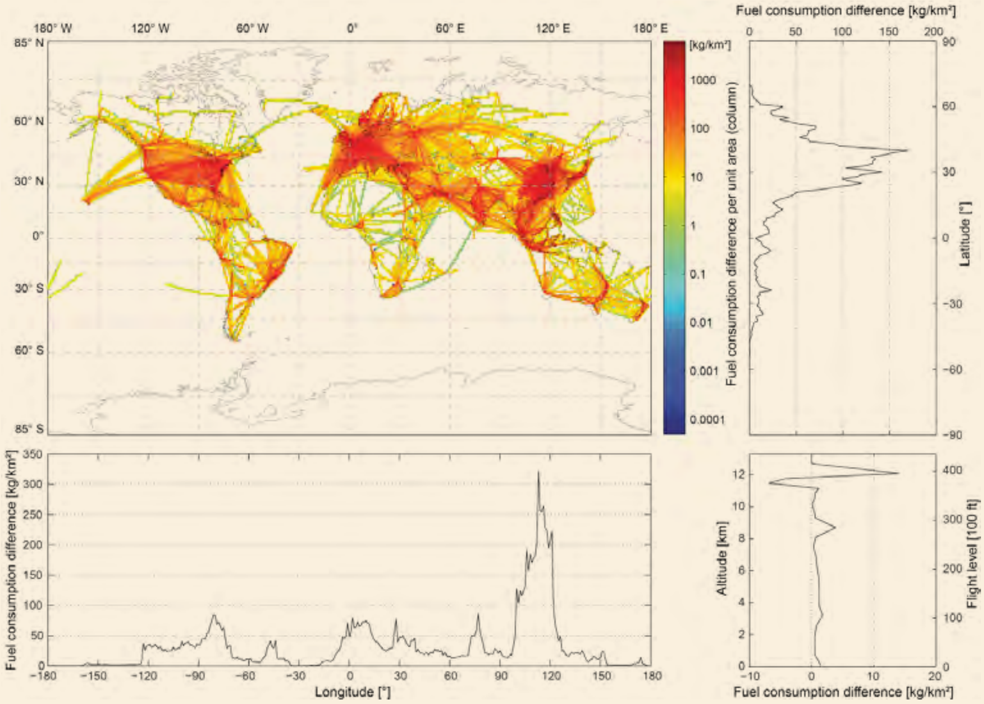

Figure 3. Fuel consumption changes in 2050 due to a SBW aircraft introduction
(positive values depict reductions with respect to business-as-usual scenario)

The altitude profile (Fig. 3, bottom right) shows that there is obviously a slight shift of fuel burn in cruise from 39000 ft altitude to lower flight levels. This phenomenon can be attributed to the slightly lower optimum altitude curves of the SBW aircraft compared to the A320. This effect will be of importance for the climate assessment presented below. The geographic distribution of the absolute NO_x emissions amounts is shown in Fig. 4. NO_x emissions primarily develop in flight phases with a high engine load, like e.g. during take-off and climb. Hence, high NO_x concentrations can be found in the vicinity of airports. Here, due to the logarithmic scale red dots could indicate future megacity locations.

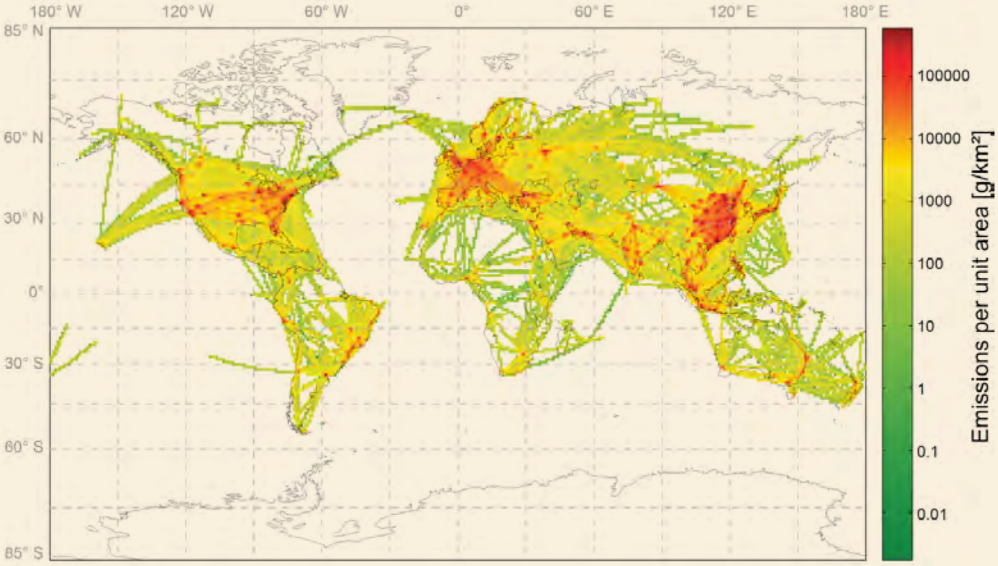

Figure 4. Absolute NO_x emission inventory of the year 2050 for a SBW scenario with a share of 93%

Using AirClim, the calculated emission inventories were finally evaluated with respect to their ATR over 100 years starting in 2015 and the SBW scenario was compared to the reference case (business as usual with today's technology level). It was found (see also Fig. 5), that the introduction of a SBW aircraft might reduce the warming associated with the air traffic growth in the seat category 100-150 seats by nearly 17%. The main driver for this is the massive reduction of NO_x emissions in combination with a slightly lower average cruising altitude (see above) leading to a reduced ozone (O_3) production. O_3 acts as greenhouse gas at those altitudes, contributing to atmospheric warming (e.g. Lee et al., 2010). Also reduced CO_2 and water vapour concentrations decrease the warming effect. As NO_x also causes methane (CH_4) depletion and methane is a greenhouse gas as well, there is also a net warming effect due to a higher methane concentration. Similarly, the primary mode ozone (PMO) contributes to an increased warming. Finally, due to the decreased average cruising altitude with more humid air, the probability of contrail formation increases which results in an additional warming. These findings are generally consistent with previous research, e.g. by Frömming et al. (2012).

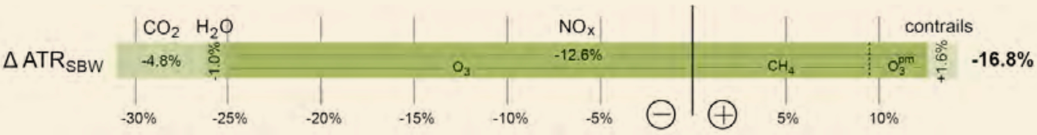

Figure 5. Relative changes in ATR due to a SBW introduction distinguished by contributing radiative forcing agents (compared to business-as-usual)

CONCLUSIONS

The results of an analysis of the global emission distribution and a climate impact assessment for the introduction of a SBW aircraft into the air transportation system have been presented. Several models developed by DLR have been applied sequentially for the study which gives an idea to what extent new aircraft configurations might contribute to a reduction of aviation's climate impact in the future. In particular, we found that the SBW aircraft has the potential to reduce the fuel consumption of the aircraft fleet of the seat category 100-150 seats by ~26% in 2050 and to decrease NO_x emissions even more by 45%. The climate impact assessment indicates, that this large reduction potential in combination with a slightly lower cruise altitude of the SBW aircraft compared to today's reference aircraft may reduce the warming caused by aircraft of that size (including the projected growth in the future) by nearly 17%. It should be noted, that the SBW design process in the FrEACs project is not yet fully accomplished and only preliminary performance data was available. The study shall be redone and results shall be adjusted as soon as a final aircraft model is ready. However, in general the obtained achievable reductions are within a plausible range and well reflect expert's expectations. Furthermore, it is important to note, that the CROR NO_x emission indices were estimated based on simplifying assumptions. A more detailed NO_x profile could be used in the future to increase accuracy. Moreover, the substitution plan that was generated by FFWD is based on the assumption that the SBW aircraft is directly used to substitute today's short-haul aircraft, which is not realistic as there is already the next generation of short-haul aircraft being introduced (i.e. A320neo, B737MAX). It would be more realistic to assume an introduction of the SBW aircraft as their successor, probably not before 2030. Future research could spend more effort in modeling also intermediate technology-levels to capture these effects.

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