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Publication date
2016

Document Version
Final published version

Citation (APA)
Grewe, V., Matthes, S., Dahlmann, K., Gollnick, V., Niklaß, M., Linke, F., & Kindler, K. (2016). *Climate impact evaluation of future green aircraft technologies*. Paper presented at Greener Aviation 2016, Brussels, Belgium.

Climate impact evaluation of future green aircraft technologies

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KEYWORDS: Climate change, Emissions, Contrails, Ozone, Methane, Mitigation Measures, Operational Measures, Technological Measures, New Configurations

ABSTRACT:

Air traffic is an important part of our mobility with an increasing rate in transport volume of around 5% per year. Air traffic also contributes to anthropogenic warming by around 5%. Here we present a climate impact assessment tool AirClim and give an overview on the recent technology assessments. Finally, we present a best practice for a robust climate impact assessment, which combines a comprehensive four-layer approach to model the air traffic system with AirClim and includes aspects of atmospheric uncertainties, sensitivities, and verification procedures.

1. Introduction

Air traffic is an important part of our mobility with an increasing rate in transport volume of around 5% per year (Lee et al., 2010). Air traffic also contributes to anthropogenic warming by around 5% (Figure 1, see also Lee et al., 2010). This warming is caused by emissions of carbon dioxide, nitrogen oxides (which influence concentration of ozone, methane and primary mode ozone - PMO), water vapour, particles and contrail-cirrus. The emitted species change the chemical and micro-physical properties of the atmosphere. Changes in the atmospheric composition alter the radiation balance, which leads to increases in global temperature. The reduction of the aviation's impact on climate is a challenge. The evaluation of the climate impact of future aviation technologies is important and requires more than estimating the total amount of emissions. For example, emissions of nitrogen oxides have a larger impact on climate when released at higher flight levels, since the atmospheric residence time of the emitted species increases and more ozone can be produced during a longer time period. Recently, we have developed a comprehensive climate impact assessment tool, which is unique with respect to the extent to which atmospheric processes and emission characteristics are taken into account. It demonstrates a major step from assessing the climate impact of aviation in general towards the climate impact assessment of individual aviation technologies and aviation options. Here, we want to demonstrate the range of possible applications and give a best practice for future climate impact assessment.

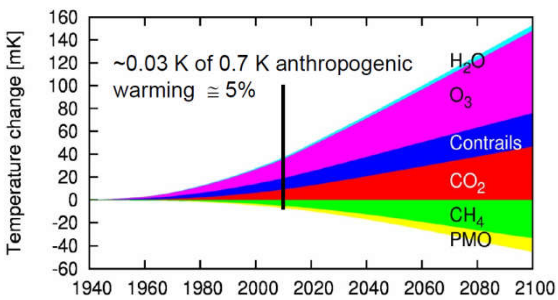

Figure 1: Global mean near surface temperature changes [mK] caused by air traffic emissions, based on AirClim calculations.

In Sec. 2 we describe the climate assessment model AirClim and give a brief overview of results concerning climate impact assessments of operational and technological measures in Sec. 3. In Sec. 4, we describe a best practice for a comprehensive climate impact assessment, e.g. for the use in CleanSky 2.

2. The climate assessment model AirClim

The climate impact assessment model is fully described by Grewe and Stenke (2008) and major recent updates by Dahlmann et al. (2016). A verification of the model is given therein as well as in Grewe and Dahlmann (2012). Here we only briefly describe AirClim (Sec. 2.1.). A speciality of AirClim is that uncertainties in atmospheric responses, e.g. as described in Lee et al. (2010), are used to derive a robust assessment by applying a Monte-Carlo simulation (Sec. 2.2).

2.1. Response functions of AirClim

AirClim is a response model. That means that first numerous simulations were performed with state-of-the-art climate and chemistry-climate models in which major aircraft emission parameters (e.g. altitude and latitude of emission) were varied. The response in atmospheric concentrations and radiation was then extracted, which basically provides the core of AirClim: Non-linear response functions between major emission parameters and effects upon the atmosphere. This is then combined with a linear response model of radiation changes on the global mean near surface temperature as described by Sausen and Schumann (2000).

2.2. Inclusion of atmospheric uncertainties

The impact of aviation emissions on the radiative forcing (= changes in the atmospheric radiation balance) is associated with large uncertainties (Lee et al., 2010). Therefore it is essential to include these uncertainties in the climate impact assessment by, e.g. Monte-Carlo simulations. AirClim provides such a feature (see Fig. 2). The response functions are defined with an uncertainty distribution and by using a Monte-Carlo-Simulation an error or uncertainty propagation is calculated. Examples are given in Sec. 3.

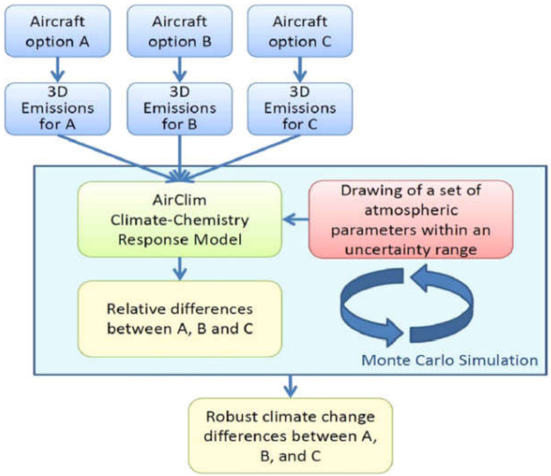

Figure 2: Sketch of a robust climate impact assessment for three different aircraft by using the Monte-Carlo-Simulation option in AirClim (Figure from Dahlmann et al., 2016).

3. Examples of climate impact assessments

In the following, we describe the potential of reducing the climate impact from aviation by applying different mitigation measures:

- Intermediate Stop Operations (ISO, Linke et al., 2016): Sec. 3.1,
- Variations of cruise altitude and speed (Koch, 2013, Dahlmann et al., 2016): Sec. 3.2,
- Supersonic-Small-Scale-Aircraft (Grewe et al. 2010): Sec. 3.3.1, and
- Multi-Fuel Blended Wing Body (MF-BWB, Grewe et al., 2016): Sec. 3.3.2.

A detailed description of these measures is given in the referenced literature. Here we only want to highlight the range of possible applications.

Note that in the following studies a significant decrease in the climate impact of aviation could only be achieved when the climate impact assessment is integral part of the aircraft operational analysis and design optimisation loop (see e.g., Grewe et al., 2016).

3.1 Operational measures

Long range air traffic operations have the disadvantage to require a large amount of fuel, which over-proportionally increase the take-off weight. ISO suggests that aircraft operators conduct intermediate landings to reduce the stage length of flights. The amount of fuel burnt over the entire mission can be reduced by refuelling the aircraft at a stopover location, because the fuel, necessary to transport the remaining fuel over a longer distance, can be omitted (Linke, 2016; Linke et al., 2016). An example for such a flight profile is given in Fig. 3.

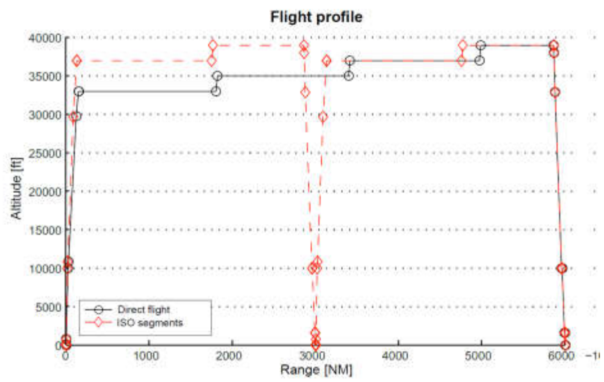

Figure 3: Change of flight altitudes due to Intermediate-Stop-Operation (ISO) shown on an exemplary 6000 NM mission flown with an Airbus A340-600 aircraft assuming an ideal intermediate landing (in the middle). Figure is taken from Linke et al. (2016).

Hence ISO reduces emissions of CO_2, H_2O and NO_x at cruise altitudes. However, assuming cost-optimized cruise the first stage of ISO has an increased cruise altitude, since the aircraft is lighter and the optimum altitude increases with decreasing weight. This results in a reduction of contrail climate effect, since fewer contrails are formed for most long-range flights, as the aircraft operates above the main contrail formation region at mid-latitudes. On the other hand the emitted NO_x and H_2O, though lower in emission magnitude, has a larger impact on climate since the residence time of these species and the effect on ozone production is enhanced (Tab. 1).

Species	Change in Climate impact [%]
CO_2	-0.7
Contrails	-0.4
NO_x	1.9
H_2O	1.3
Total	2.3*

*Table 1: Relative change [%] in the climate impact, measured as the 100 year mean change in global near surface temperature after the introduction of ISO calculated with AirClim. *Rounding errors lead to a deviation of the total. Data are taken from Linke (2016) and Linke et al. (2016).*

3.2 Operational-technological measures

Another operational measure is changing flight altitude and speed in order to reduce the climate impact from non-CO_2 emissions, which have a pronounced altitude dependency. Koch (2013) and Dahlmann et al. (2016) have performed a detailed climate impact analysis for a large variety of cruise altitudes and speeds for an Airbus A330-200 with its route network from the year 2006. Fig. 4 shows the changes in climate impact measured as the change in the near surface temperature over 100 years after introduction of this operational change, versus the increase in operating costs. For an eco-efficient situation, i.e. where the ratio between temperature change and cost increase is favourable, a clear decrease in the climate impact of around 30% (=0.7) and an increase in costs of around 5% is found.

Since the aircraft under these conditions operates off design, the aircraft was redesigned for this new lower cruise altitude and speed, which in the end represent an operational-technological mitigation measure. Fig. 5 shows the re-design (left) and the new Pareto front (right). The dashed line shows the Pareto front of the original aircraft, whereas the solid line shows the Pareto front of the re-designed aircraft. Clearly, due to the re-design, the drawbacks of the increased operational costs can be compensated and a relation of a 30% reduction in climate with no additional operational costs is derived.

Note that uncertainties from atmospheric science are taken into account by a Monte-Carlo-Simulation and the uncertainty ranges are represented in Fig. 4 by horizontal bars.

The results vary by roughly ±10%, but the major results presented above are not altered.

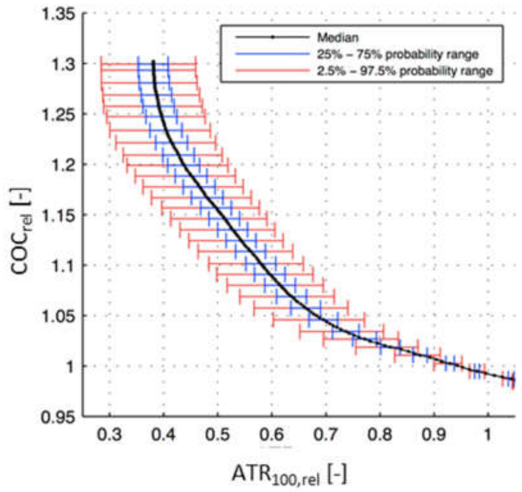

Fig. 4: Optimal relation between climate impact reduction relative to the 2006 real flight scenario (x-axis) and the respective increase in costs (y-axis) for the 2006 fleet of A330 aircraft. Climate impact is expressed as changes in the average temperature response over 100 years (ATR100). Bars indicate uncertainty ranges from atmospheric science. Figure is taken from Koch (2013) and Dahlmann et al. (2016).

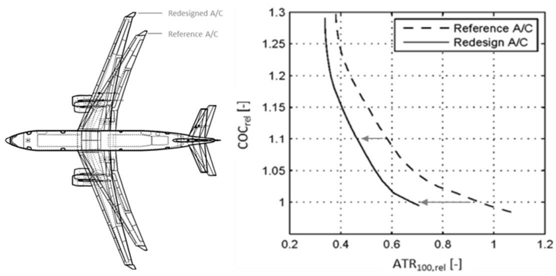

Fig. 5: Left: Changes in the design of the A330 aircraft due to a new design point. Right: Optimal relation between climate impact reduction relative to the real performed operations and the respective increase in costs for the 2006 fleet of A330 aircraft for the original aircraft (dashed line) and the redesigned aircraft (solid line). Figures are taken from Koch (2013) and Dahlmann et al. (2016).

3.3 Technological measures

3.3.1 A supersonic small scale aircraft

Within the European project HISAC three supersonic business jets were investigated, which were optimised with respect to noise, range, and sonic boom (Grewe et al., 2010; Fig. 6) based on a common configuration, which was also optimised with respect to climate impact. Fig. 6 shows drawings of the three aircraft and compares their climate impact to a reference case. The results show that the noise-optimised aircraft also has the lowest climate impact, whereas the aircraft optimised for low sonic boom has the largest climate impact.

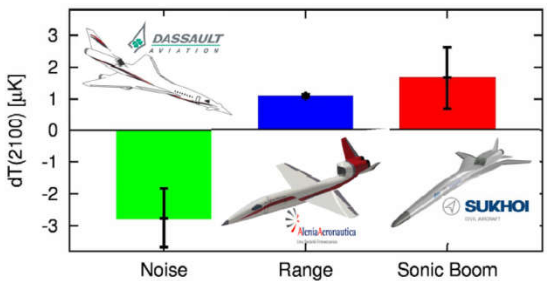

Figure 6: Climate impact of fleets of three different small-scale supersonic aircraft. Bars indicate uncertainty ranges from atmospheric science. Figure adapted from Grewe et al. (2010).

3.3.2 Multi-fuel blended wing body

Within the European project AHEAD the feasibility of a multi-fuel blended wing body (MF-BWB) was investigated as an option for fuel independency and climate mitigation (Rao et al. this issue and Rao et al., 2014). A two stage combustion chamber was developed, in which first liquid hydrogen (LH2) or liquid natural gas (LNG) is burnt and second bio kerosene is burnt flameless. This combustion approach largely reduces CO_2 and non-CO_2 emission.

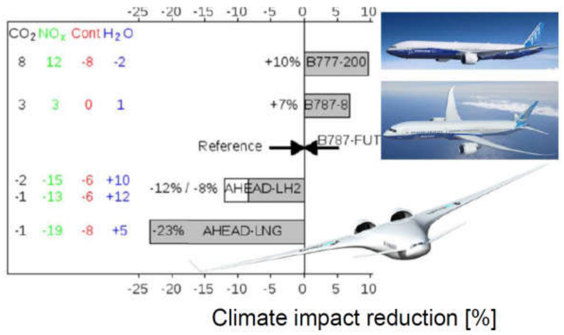

Fig. 7: Change in climate impact of a future (2050) multi-fuel blended wing body, fuelled either with liquid hydrogen and bio kerosene (AHEAD-LH2) or liquid natural gas and bio kerosene (AHEAD-LNG). The Boeing B787-8 with some envisaged future enhancements is taken as a reference (B787-FUT) and two current aircraft are included as well. Figure adapted from Grewe et al. (2010).

Fig. 7 shows the results of the climate impact assessment for two versions of the AHEAD MF-BWB in comparison to a reference future conventional configuration and some present day aircraft. A significant climate impact reduction was achieved with this technology.

4. Best practice for a robust climate impact assessment: A comprehensive DLR approach

Based on lessons learnt, we will motivate our comprehensive DLR approach for a robust climate impact assessment.

4.1 Lesson learnt

The examples presented in Sec. 3 show the wide range of performed assessments of climate mitigation measures. During the course of the related projects important lessons were learnt:

1. <u>Climate assessment as integral part of new developments</u>:
   Feedback between aeronautical engineering and climate science is essential to avoid, as early as possible, developments which might increase the overall climate impact (CO_2 plus non-CO_2 effects), though potentially reducing the CO_2 emissions. Note that an early re-adjustment is also economically advanta-geous.
2. <u>Reasonable aviation scenario</u>:
   Any climate assessment requires a thorough consideration of where the aircraft might be operated. The climate effect of aviation differs whether the aircraft flies at higher or lower altitudes, or at mid latitudes or tropics. See Sec. 4.2 for more details.
3. <u>Adequate climate metrics</u>:
   A thorough consideration of what we aim to assess is essential for any climate assessment. A clear formulation of the objective defines a limited set of climate metrics, which then should be used (Grewe and Dahlmann, 2015).
4. <u>Robust climate assessment</u>:
   The effects of aviation upon the atmosphere are associated with uncertainties. Making decisions on the grounds of uncertain data is not unique to atmospheric science and decisions based on uncertain data have to be taken all the time in our lives. Therefore we have to include these uncertainties in the assessments, e.g. by applying Monte-Carlo simulations, and provide a verification strategy (see Sec. 4.3 for details). The necessity of reducing the uncertainties remains of course unaffected.

4.2 Modelling the future Air Transportation System

The heterogeneous socio-economic growth in world regions is expected to induce shifts of deployed seat categories, shifts of distances flown by seat categories, and geographical shifts of aircraft movements and resulting emission inventories worldwide. These anticipated changes of the location of aircraft emissions will strongly influence the future climate impact of aviation's non-CO_2 effects. In order to assess the climate compatibility of possible future ATS evolutions – including various combinations of technological and operational mitigation options – a geospatial simulation of future aircraft movements over time is required. Current and future air transportation systems have to be analysed, modelled, or even "designed".

The DLR project "WeCare" made big progress towards developing and implementing the idea of modelling the future ATS on a global scale.

Within this project a modular assessment framework was built that grounds on a generic 4-layer philosophy and the use of exogenous socio-economic scenarios (see Fig. 7):

(1) Passenger demand network (Terekhov et al., 2015)
(2) Passenger routes network (Schittenhelm and Kölker, 2015)
(3) Aircraft movements network (Kölker et al., 2015)
(4) Emission inventories and trajectories network (Linke et al., 2016)

Besides climate impact assessment, the framework has been used

(i) to deduce top level aircraft requirements by analysing range-size market relationships,
(ii) to identify future bottlenecks of aviation infrastructures,
(iii) to conduct market analyses for strategic airline planning,
(iv) to perform studies on the efficiency of new technological and operational concepts, or
(v) to produce global air traffic emission inventories for different traffic scenarios.

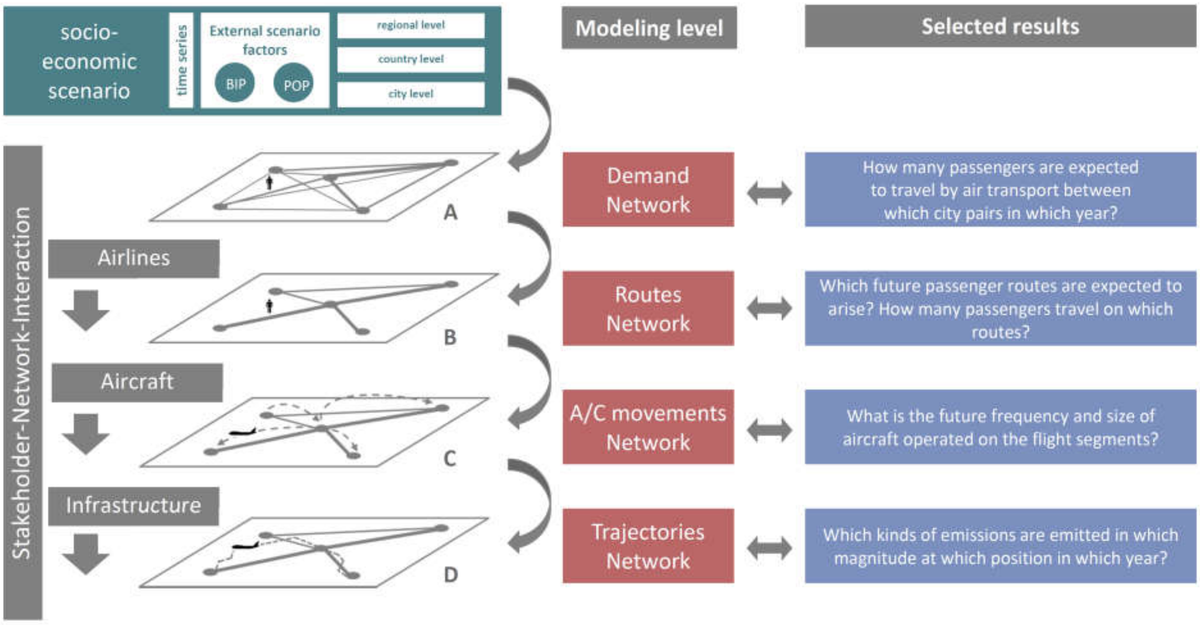

Figure 7: Modelling the future air transportation system based on the 4-layer philosophy. Figure adapted from Ghosh et al. (2015).

4.3 Climate impact assessment

The four-layer air traffic system modelling approach, presented in Sec. 4.2 and Fig. 7, is a key input to a robust climate impact assessment with e.g. the climate-chemistry response model AirClim (Fig. 8). Feedback loops with technology providers (CS2 in this example, upper left in Fig. 8) are essential to provide preliminary or first assessments and identify major impacts at an early stage in order to adapt the technology accordingly.

The climate impact assessment platform has to be flexible enough to include those atmospheric processes (upper right box in Fig. 8), where the understanding became mature enough. An example for such a process is the effect of emitted soot particles on natural cirrus clouds or even the formation of cirrus (Kärcher et al., 2007). Note that this is a different process than contrail formation and their spread into contrail-cirrus. Contrails form, if during the mixing of the exhaust with the environment, saturation with respect to the liquid phase is reached and the air is cold enough to freeze the water droplets.

A key aspect of a climate impact assessment is the inclusion of uncertainties and sensitivities. AirClim has the ability to explore the impact of a wide range of parameter settings on the climate impact assessment. By this, we obtain uncertainty ranges of the climate impact (see e.g. Sec. 3). This provides a thorough basis for a risk analysis.

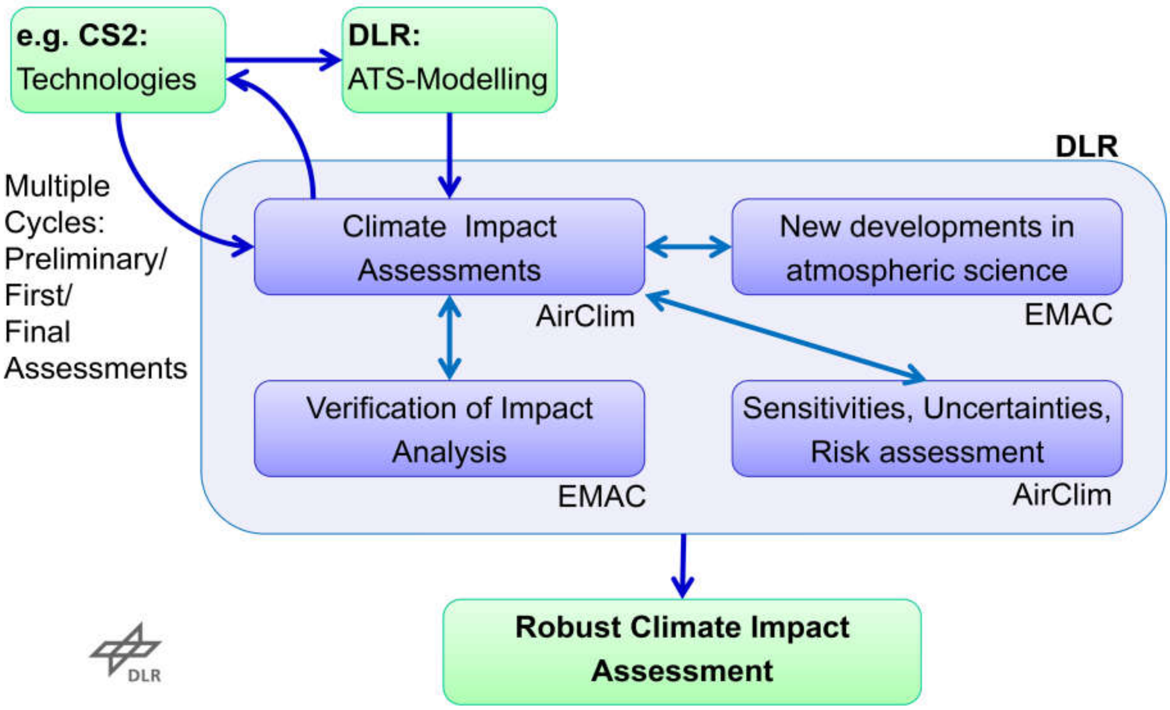

Figure 8: Best practice for a robust climate impact analysis.

In the end, ideally after multiple iterations with technology providers and hence numerous applications of the AirClim model, it is most desirable to define a final technology emission scenario based on the 4-layer philosophy (Sec. 4.2) with which the response modelling results are verified on the basis of high fidelity models, e.g. the Earth-System Model EMAC (Jöckel et al., 2016; Bock et al., 2016, lower right box in Fig. 8).

These four parts, the climate impact assessment, the ability to include new upcoming processes, the assessment of uncertainties and sensitivities, and the verifications of the final results in close cooperation with the technology provider, provides in combination with the air traffic system modelling a robust climate impact assessment of new aviation technologies.

5. Summary

We have presented an overview on recent climate impact assessments of operational and technological mitigation measures. The assessments are based on response modelling, which reflect the current state-of-the-art Earth-System models – a unique modelling approach.

Based on the experience gained during these applications, we defined a best practice, which includes the possibility to adapt the response model, e.g. by including not yet considered atmospheric processes, such as the soot-cirrus effect (Kärcher et al., 2007), whenever they become mature enough. Uncertainties in atmospheric processes are considerable and have to be incorporated in any climate impact assessment. However they are not compromising or limiting a climate assessment in principle, but have to be integral part of it. The response modelling is a computational efficient tool and the results largely reflect those obtained from detailed modelling (Dahlmann et al., 2016, Grewe and Dahlmann 2012). However, a verification of the final results by detailed process modelling is required for robust climate impact assessments.

The best practice advises the inclusion of climate impact assessments in the pre-design of new aircraft, to avoid developments which increase the overall climate impact although they might be more fuel efficient. Non-CO_2

effects might easily compensate positive effects on climate which are related to an increase of the fuel efficiency.

The combination of a detailed air transportation system modelling with a comprehensive climate impact assessment modelling comprises a sound and unique modelling framework for a robust climate impact assessment for new aviation technologies.

This approach forms a basis for the development of low-climate-impact aircraft configurations. It can then be combined with operational measures on a day-to-day basis, which reduce the climate impact by e.g. avoiding climate sensitive regions, such as regions where strongly warming contrails form, or nitrogen oxide emission lead to large amounts of the greenhouse gas ozone (Schumann et al., 2011, Matthes et al., 2012, Grewe et al., 2014).

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