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How to best address aviation's full climate impact from an economic policy point of view? – Main results from AviClim research project

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ABSTRACT

The interdisciplinary research project AviClim (Including Aviation in International Protocols for Climate Protection) has explored the feasibility for including aviation's full climate impact, i.e., both long-lived CO_2 and short-lived non-CO_2 effects, in international protocols for climate protection and has investigated the economic impacts. Short-lived non-CO_2 effects of aviation are NO_x emissions, H_2O emissions or contrail cirrus, for instance.

Four geopolitical scenarios have been designed which differ concerning the level of international support for climate protecting measures. These scenarios have been combined alternatively with an emissions trading scheme on CO_2 and non-CO_2 species, a climate tax and a NO_x emission charge combined with CO_2 trading and operational measures (such as lower flight altitudes). Modelling results indicate that a global emissions trading scheme for both CO_2 and non-CO_2 emissions would be the best solution from an economic and environmental point of view. Costs and impacts on competition could be kept at a relatively moderate level and effects on employment are moderate, too. At the same time, environmental benefits are noticeable.

Introduction

Aviation contributes to climate change by both CO_2 and non-CO_2 effects, such as ozone and methane changes from NO_x emissions or contrails and contrail cirrus: In 2005 aircraft-induced CO_2 contributed 1.6% to the total anthropogenic radiative forcing (Lee et al., 2009), while the total aviation effect, i.e., the sum of the CO_2 and the non-CO_2 effects, amounted to 4.9%. During the next decades international aviation is expected to grow significantly (e.g., ICAO, 2013a). While international aviation's carbon dioxide emissions have been regulated in several countries in the recent years, this is not the case for most of aviation's non-CO_2 climate effects. To complicate matters, aviation-induced clouds and the effects of NO_x emissions at cruise altitudes are neither fully understood from an atmospheric sciences point of view nor investigated with regard to the possible introduction of regulatory measures at this point.

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The international character of aviation renders national approaches ineffective and requires lengthy political negotiations on the international level. Here, both the International Civil Aviation Organisation (ICAO) which is the UN agency responsible for international civil aviation, and any supranational/international political institution of greater regional importance such as the European Commission will have to be involved. With regard to expected future annual growth rates of about 5% on average (ICAO, 2013a), the implementation of global or at least internationally coordinated instruments for the reduction of the non-CO_2 impact of international aviation on climate change seems to be necessary expeditiously.

How can international aviation be best included in international protocols for climate protection from an economic point of view? This question has been addressed by the research project AviClim (Including Aviation in International Protocols for Climate Protection), funded by the German Bundesministerium für Bildung und Forschung (BMBF), see Scheelhaase et al. (2015) for the final report of this project. The present paper is organized as follows: section 'Impact of aviation on climate and regulatory measures to mitigate this impact' provides an overview of the impact of aviation on climate and the current regulatory measures to mitigate this impact. Section 'Methodological approach' summarizes AviClim's methodological approach. Section 'Main results' presents and discusses the main economic and environmental results. Section 'Summary and recommendations' provides conclusions and recommendations.

Impact of aviation on climate and regulatory measures to mitigate this impact

Impact of aviation on climate

The impact of aviation on climate is often described in terms of radiative forcing (RF), which is a measure for the perturbation of the Earth's natural radiative equilibrium due to the cumulative effect of a (mostly) anthropogenic change of the atmospheric composition relative to the pre-industrial state (e.g., IPCC, 1999). The expected new equilibrium (near) surface temperature change ΔT is to first order proportional to RF if the change of the atmospheric composition remains constant. A positive RF results in a warming, while a negative RF results in a cooling of the climate.

Radiative forcing from aviation is composed of several components. CO_2 with an atmospheric lifetime up to millennia and H_2O with a lifetime between hours and months contribute to a positive RF. The NO_x emissions have several effects: On a rather short timescale, ozone (O_3) is formed via smog reactions (warming effect) with a lifetime in the range from weeks to months. As a secondary effect, methane (CH_4) in the atmosphere is destroyed (cooling effect) with a lifetime of about a decade. Finally, from the reduced methane a secondary reduction of the ozone concentration results (cooling effect), which has the same lifetime as methane. In total, the RF from NO_x is positive (warming). Individual contrails (line-shaped high altitude clouds triggered by the aircraft water emissions) and the associated contrail cirrus (cirrus clouds evolving from contrail at suitable atmospheric conditions) may warm or cool the atmosphere, depending on daytime, cloud properties and the reflectivity of the surface underneath the contrail or contrail cirrus. On global and annual average these cloud effects result in a positive RF, which is of a similar magnitude than the RF from CO_2 (e.g., Lee et al., 2009, 2010; Burkhardt and Kärcher, 2011).

Different to most sectors of human activity, aviation's non-CO_2 effects play an important role and contribute about 2/3 of the total aviation forcing (Lee et al., 2009). Contrary to CO_2 emissions, aviation's non-CO_2 effects depend on flight altitude, geographical location, day time, weather situation, etc. (e.g., Fichter et al., 2005; Mannstein et al., 2005; Fichter, 2009; Frömming et al., 2012). Due to the different lifetimes and due to the spatially dependent impacts, the climate change induced by the aviation non-CO_2 effects is not proportional to the CO_2 emissions. Therefore, accounting aviation's non-CO_2 effects by simply applying a factor to the CO_2 emissions, as suggested by, e.g., the European Parliament, is not appropriate as it would provide incorrect incentives (see also Forster et al., 2006).

Currently, the science community discusses how to weigh short-lived non-CO_2 effects in relation to CO_2 (e.g., Fuglestvedt et al., 2010; Deuber et al., 2014). As mentioned above a simple (constant) factor on CO_2 is inadequate. Calculating the individual contributions to RF is an important method to understand the climate impact of aviation but offers no tool for mitigating future aircraft effects. As a "backward looking" tool RF accounts for the emissions of the past and not for future emissions. For long-lived species, such as the species regulated by the Kyoto Protocol, equivalent CO_2 on the basis of the Global Warming Potential (GWP, time integrated RF) proved to be a suitable tool (e.g., Fuglestvedt et al., 2010). However, this metric has severe deficits when considering short-term climate impacts. Up to now, no consensus has been reached on the most appropriate metric. But the choice of this metric is not arbitrary; it should be followed from the application it is used for (Grewe and Dahlmann, 2015). For the present study, the Average Temperature Response (ATR), which is the mean temperature change over a time horizon of 20 and 50 years (atr_20 and atr_50) turned out to be a suitable metric to compare non-CO_2 effects among each other and with CO_2 (Dahlmann, 2012).

Regulatory approaches to limit aviation's impact on climate

Which regulatory approaches for the limitation of aviation's impact on climate would be beneficial from an environmental economics theory point of view? How are some of aviation's climate relevant emissions regulated currently? These questions are discussed in the following section.

Environmental economics theory has shown decades ago that market-based measures based on marginal cost pricing (e.g., taxes, charges and emissions trading) can lead to considerable benefits compared to rather traditional 'command-and control' politics, see for instance Dales (1968) or Siebert (1976). Compared to 'command-and-control' approaches, these economic instruments are generally characterized by reaching environmental targets very cost-efficiently (see for instance Nordhaus, 1982).

Against this background the implementation of a charge on non-CO_2 species, possibly combined with other instruments could be considered among other options. In 2008, charges on aviation's local NO_x emissions combined with a distance factor were proposed by some economists (CE Delft, 2008). Another possible instrument would be the trading of emissions allowances for aviation's climate relevant species. This requires the transformation of the non-CO_2 effects in equivalent CO_2 according to a suitable metric. Also, a tax on climate relevant species could be a viable option. In addition, operational measures such as climate optimized flight trajectories (Grewe et al., 2014 and Soler et al., 2014) could be worth considering. Both charges and emissions trading are currently or will soon be applied for limiting some of aviation's climate relevant emissions in a number of countries:

In Europe, aircraft emission charges on local NO_x and hydrocarbon (HC) emissions have been applied since the late 1990s. Sweden started in 1997, Switzerland followed in 1998 (Unique AG, 2003). The UK airports London Heathrow and London Gatwick acted accordingly in 2004 and 2005. Copenhagen Airport followed in 2010. In Germany, local charges on NO_x and HC emissions have been introduced at the airports of Frankfurt, München, Köln-Bonn, Hamburg, Düsseldorf and Stuttgart in the timeframe 2008–2013. The introduction of the charge is understood as a pilot phase with airports participating on a voluntary basis. After this phase, the environmental and economic impacts of the charge should be investigated and the design of the charge may be subject to modifications (Scheelhaase, 2010). To date, the environmental effects of the aircraft emission charges have not been investigated quantitatively in any European country.

The charge in the abovementioned European countries regulates NO_x and HC being emitted during the landing- and take-off-cycle (Unique AG, 2003). NO_x and HC are the main contributors to combustion-related local air pollution and precursors of ground level ozone. A positive side-effect of the charge on local NO_x emissions is that it will also reduce greenhouse gas effects to a certain extent: Because more NO_x friendly engines are used, the amount of emitted NO_x will be reduced at cruise level as well as below 3000 feet during the LTO cycle. However, it has to be taken in mind that a trade-off exists between the reduction of NO_x and CO_2 emissions (Daley, 2010 and Szodruch et al., 2011). Most aircraft engines available today can technologically be optimized either to minimize fuel burn, and thus CO_2 emissions, or to minimize NO_x emissions (Rosskopf et al., 2014).

At the level of the European Union (EU), the European Commission has been analysing since 2008, whether NO_x charges can be an appropriate instrument to reduce the non-CO_2 climate impact of international aviation (Scheelhaase, 2010). Measures under consideration include local NO_x charges modified by a distance factor, en-route NO_x charges, an increased NO_x stringency for LTO emissions standard and a multiplier on CO_2 emissions (CE Delft, 2008). This approach is part of the general EU strategy to examine the full range of external costs for all modes of transport, to analyse the impact of the internalization of external costs and to prepare a stepwise internalization programme for the EU (Council of the European Union, 1999; Commission of the European Communities, 2001).

In the timeframe 2008 until 2015, a number of emissions trading schemes tackling climate change on a national as well as on a supranational level have been or will soon be introduced. Among other sectors, aviation has been addressed as well. However, the trading schemes are designed rather differently (Scheelhaase, 2011, 2014).

In the European Union, an emissions trading scheme (EU ETS) for the reduction of CO_2 emissions from stationary sources was introduced in 2005. In 2012, international aviation has been fully integrated into this trading scheme (Council of the European Union, 2009a,b). The scheme covers all flights departing from or arriving at airports in the European Union, Norway and Iceland (=European Economic Area, EEA). This way, both European and non-European airlines are addressed by the regulations of the trading scheme. In this scheme, aircraft operators are obliged to hold and surrender allowances for CO_2 emissions (Anger and Köhler, 2010).

At the International Civil Aviation Organisation (ICAO) Assemblies 2007, 2010 and 2013, strongly diverting views of non-EU countries were expressed concerning the EC Directives for the inclusion of air transport into the EU ETS. Contrary to the EU Member States and the EU Commission, most other ICAO Contracting States believe that an inclusion of non-EU airlines is only possible on the basis of mutual agreements which do not exist to date. In many countries opposed to the EU ETS, countermeasures and restrictions on European airlines have been prepared, such as special taxes and traffic rights limitations (Bartels, 2012). At the 38th ICAO Assembly in September/October 2013, the ICAO Contracting States agreed to develop a global scheme for the regulation of international aviation's CO_2 emissions by the year 2016 and to introduce it by 2020 (ICAO, 2013b). As of July 2015, the CO_2-regulation scheme is not defined yet, and most favourable options are an emissions trading or an offsetting scheme.

Against this background, the Council of the EU and the EU Parliament agreed to limit the geographical coverage of the EU ETS to emissions from all flights within the European Economic Area (EEA) for the period from 2013 to 2016, until after the ICAO Assembly (Commission of the European Union, 2014).

In 2008 New Zealand introduced a national emissions trading system for the reduction of greenhouse gas emissions (New Zealand Government, 2014). Until 2013, several sectors have been gradually phased in the trading scheme. The first sector under the trading scheme was the forestry sector which started trading in 2008. By 2010, the liquid fossil fuels sector as well as the stationary energy and industrial processes sectors have become mandatory participants. The waste sector and the importers of 'synthetic' greenhouse gases (HFCs, PFCs and SF_6) followed in 2013. Contrary to the original intention, agriculture only has reporting obligations in the scheme due to cost-containment reasons. Transport including domestic aviation has been addressed indirectly by a so-called upstream approach: The liquid fossil fuels sector is expected to pass through the costs of compliance to the aircraft operators in the form of increased kerosene prices (Scheelhaase, 2014). Fuels used for international aviation (and marine transport) are exempt from the scheme.

According to the 12th Five Year Plan of 2011, China is planning to introduce a national carbon trading system (Government of China, 2011). By 2016, the main emitting sectors of CO_2 will be included. Among other sectors, domestic aviation will be participating. By implementing a national CO_2 trading scheme, China intends to reduce its growing demand for fossil fuels and to limit the local and global impacts of energy related emissions (IETA, 2013). In order to find suitable solutions for a Chinese national trading scheme, seven regional carbon trading pilot systems are currently being tested (Chang and Wang, 2010; Stockholm Environment Institute/FORES, 2012). Apart from stationary sources in particular the Shanghai pilot trading scheme requires six Shanghai based airlines to submit emission permits for their domestic operations. The EU will provide expertise in setting up China's national emissions trading system (European Voice, 2012).

In January 2015, South Korea introduced a national emissions trading scheme for the limitation of greenhouse gases. With a cap of 573 $MtCO_2$-equivalent in 2015, it is the second largest emissions trading scheme in the world after the EU ETS (ICAP, 2015). It covers about 60% of the national greenhouse gas emissions in the Kyoto basket (CO_2, CH_4, N_2O, HFC, PFC, SF_6). In the Korean scheme the sectors steel, cement, petro-chemistry, refinery, power, buildings, waste sectors and domestic aviation are included (ICAP, 2015). Installations emitting more than 25,000 t CO_2-equivalent per year and entities emitting over 125,000 t CO_2-equivalent per year are included on a mandatory basis. Other installations are allowed to opt-in on a voluntary basis (Yong-Gun, 2012). Linking arrangements with the European and the New Zealand trading schemes are planned by the Korean Government (Europolitics, 2012).

Overall, the global framework for the limitation of aviation's climate relevant emissions is diverse. And until now, the non-CO_2 species have only been addressed scarcely both on ICAO and on a national level. Due to urgent environmental needs, the political regulation of the full climate impact of aviation is strongly recommended in the foreseeable future.

AviClim's methodological approach

Scenarios and market-based measures investigated

How can aviation's full climate impact, i.e., the CO_2 and the non-CO_2 effects, best be regulated from an economic point of view? In order to investigate this question, four geopolitical scenarios (Fig. 1) have been designed, which differ in concerning the level of international support for climate protecting measures in aviation. This way, the environmental and economic impacts of different and in consideration of current political negotiations likely geopolitical coalitions can be investigated:

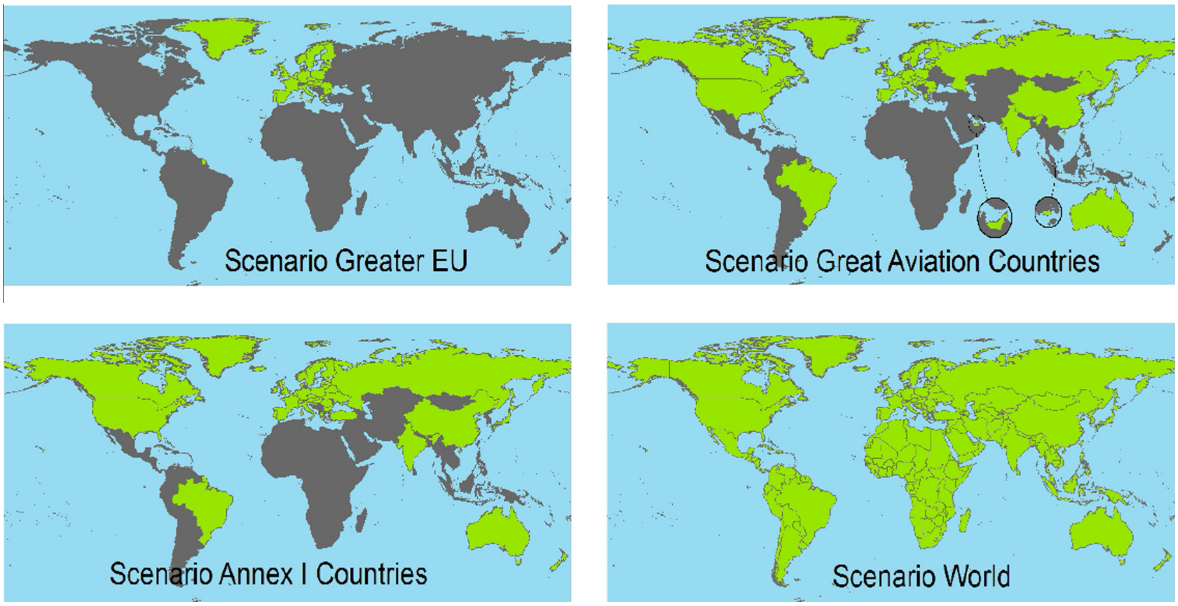

Fig. 1. Groups of countries that apply the different regulatory measures assumed in the geopolitical scenarios. Countries marked in GREEN are supporting the assumed market-based measure for regulating aviation's climate relevant emissions in the scenario investigated. The blow-ups in "Scenario Great Aviation Countries" show the United Arab Emirates and Singapore, respectively. The "Scenario Annex I Countries" also comprises the BRIC countries. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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– Scenario "Greater EU" represents more or less today's geopolitical support for an emissions trading scheme limiting international and national aviation's CO_2 emissions. As explained above, international aviation has been included in the EU emissions trading scheme in 2012. Norway, Iceland and Liechtenstein are participating in this scheme.
– Scenario "Great Aviation Countries" assumes that the main players in international and national aviation were supporting the market-based measure under consideration. This way, the main emitters of climate relevant species from aviation could be addressed.
– Scenario "Annex-I Countries" supposes that the countries which supported the Kyoto protocol in 1997 (so-called "Annex-I Countries") plus the BRIC countries (Brazil, Russia, India and China) would introduce the respective market-based measure in air transport.
– The geopolitical scenario "World", finally, supposes a global support for the climate protecting instrument under consideration. Clearly, this would be the best solution from an environmental stand-point as all climate relevant emissions would be fully included. But negotiations in the past decades have shown that a global solution is very difficult to find.

Each of these geopolitical scenarios will be compared with a Business-as-usual Scenario which assumes a continuation of the current climate protecting policies.

The four geopolitical scenarios have been combined with selected market-based measures for the reduction of aviation's climate relevant emissions which have been chosen in respect to economic efficiency, potential environmental benefits and practicability. Market-based measures analysed include the following:

– an emissions trading scheme for regulating all climate relevant emissions from aviation,
– a climate tax for all climate relevant emissions and
– a NO_x emission airline charge combined with a CO_2 trading scheme and operational measures. Operational measures assume that 50% of flights operated between 30°N and 60°N and on an altitude between 28,000 and 38,000 feet (about 9 and 12 km) will be flying 2000 feet (about 630 m) lower to reduce contrails and contrail cirrus. The additional fuel burn resulting from a reduced flight altitude has been considered according to Fichter (2009).

Within AviClim it has been generally assumed that the commercial airline operators will be the accountable entities of the market-based measure under investigation. Furthermore, it has been assumed that all flights to, from and within the countries belonging to the respective geopolitical reduction scenario will be subject to the climate protecting political regulations, regardless of the airline's country of origin. This means, for instance, that an US carrier in the scenario "Greater EU" will have to fulfil the obligations of the climate tax for all flights to and from the countries of the "Greater EU" scenario, even though the US government is not supporting the market-based measure in this geopolitical scenario.

Models employed

Fig. 2 provides an overview of the AviClim modelling approach.

Our modelling grounds on the forecast emission inventory. The absolute amount of the CO_2 emissions of aviation in the timeframe 2010–2030 differentiated by the different geopolitical scenarios and years has been calculated by means of the DLR tool VarMission (Schaefer, 2012; Schaefer et al., 2010). The use of such a tool was essential since no detailed and publicly available statistics on this issue exist to date. Data basis was the global empirical flight plan data provided by Official Airline Guide (OAG) timetables and complementary DLR developed flight plans for the future.

To compare the impact of CO_2 emissions and non-CO_2 effects we used CO_2 equivalence factors which are calculated with the response model AirClim (e.g., Dahlmann, 2012; Grewe and Dahlmann, 2012; Dahlmann et al., 2015). AirClim combines pre-calculated, altitude and latitude dependent perturbations with emission data in order to calculate

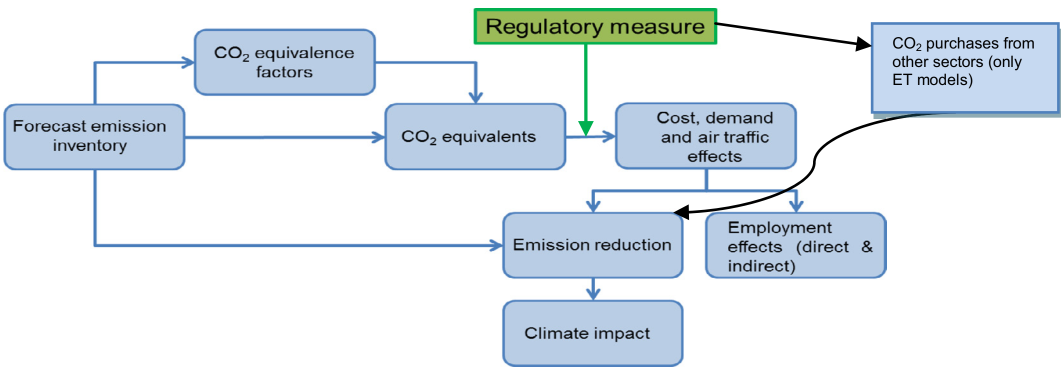

Fig. 2. Schematic of the AviClim modelling approach.

composition changes, radiative forcing (RF) and near surface temperature changes (ΔT) caused by these emissions, where near surface temperature change is presumed to be a reasonable indicator for climate change (Grewe and Stenke, 2008). AirClim calculates the climate impact of different climate agents (CO_2, H_2O, NO_x ($O_3 + CH_4 + O_3^{pm}$) and CiC (Contrail induced Cloudiness, i.e. line-shaped contrails and contrail cirrus)) in dependency of the emission location. To find a reasonable compromise between calculation effort and accuracy of the results we decided to use only an altitude dependency of the climate impact. Nevertheless we use horizontal emission distributions of nowadays air traffic to calculate the climate impact. Therefore we calculated the impact of air traffic for each flight level separately. Then we got the CO_2 equivalents by calculating the impact of each species per kg emission or flown distances relative to the impact of one kg CO_2. To this end we used the Average Temperature Response (ATR) with a time horizon of 20 and 50 years, respectively, to compare the climate impacts. As mentioned above, ATR is the mean change in near surface temperature averaged over 20 and 50 years, respectively. The CO_2 equivalence factors which in particular depend on flight altitude are shown in Fig. 3 for atr_20 and atr_50, respectively. An emission of 1 kg NO_x in an altitude of 30,000 feet, for example, has the same impact on climate over 20 years as 700 kg CO_2.

The forecast emission inventory was combined with the CO_2 equivalence factors to calculate the associated amounts of CO_2 equivalents of the non-CO_2 species for each flight. For simulating the distribution of all climate relevant emissions in three-dimensional space (longitude, latitude and altitude) and time, the newly developed and validated calculation model 4D-Race (4 Dimensional distRibution of AirCraft Emissions) has been employed. This model generates air traffic emission inventories to serve as a basis for determining climate effects. It detects not only long-lived CO_2 emissions, but also corresponding emissions of short-lived air pollutants such as NO_x, SO_x and soot.

The regulatory measure assumed will affect the costs of the airlines under the respective scheme. Important parameters for the costs of the market-based measures include the amounts of CO_2 equivalent emitted on the flights under the climate protecting measure and the prices for CO_2 equivalent. As the future development of prices for CO_2 equivalent is difficult to foresee, three different price development paths have been assumed: (1) A 'High Price Path', (2) a 'Low Price Path' with a price range of 10 USD per ton CO_2 equivalent in the year 2010 (both Price Paths) to 80 USD per ton in 2030 for the 'High Price Path' and 30 USD for the 'Low Price Path', respectively, and (3) the 'Mixed Price Path' which assumes low CO_2 equivalent prices for both trading schemes (trading of all climate relevant species and CO_2 trading) and high prices for the climate tax and the NO_x charge. This way, the likely advantage of trading schemes which becomes manifest in lower emission prices (as compared to taxes and charges) can be shown more explicitly.

In brief, the modelling of the costs of the market-based measures has been conducted by the following consecutive steps. A detailed description is provided by Scheelhaase et al. (2015). At first, the revenue ton kilometres (RTKs) subject to the market-based measure have been estimated for the years 2010–2030 on a flight-by-flight and yearly basis. Second, the associated CO_2 and non-CO_2 emissions have been modelled by employing the models explained above. In these models, fuel efficiency improvements of about 1.4 per cent per annum have been assumed. The absolute amounts of CO_2, NO_x, H_2O, etc. in tons result. Third, the climate relevant emissions subject to the respective geopolitical reduction scenario are multiplied by the specific altitude dependent metric for CO_2, NO_x, H_2O, etc. The summation of these terms forms the total amount of CO_2 equivalent (in tons) under the geopolitical scenario investigated.

The three market-based measures investigated are designed differently in order to identify the most promising design options in respect to economic and environmental efficiency: The climate tax charges the total amount of all climate relevant species from the first unit emitted. The NO_x charge, which will be combined with CO_2 emissions trading and operational measures as has been explained above, puts a price on the NO_x emissions from the first NO_x unit emitted. In contrast, for both trading schemes (trading scheme for all climate relevant emissions and CO_2 trading scheme, respectively) a free allocation of 85% of 2010 emissions has been assumed. This assumption was inspired by the free allocation rule in the EU ETS. Applying these rules, aviation's free emissions are capped to 2010 levels under the emissions trading schemes. For any

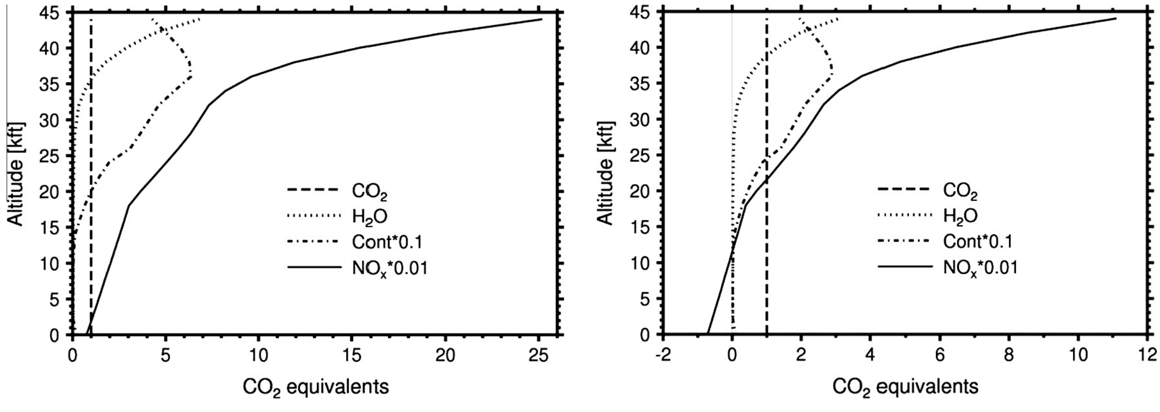

Fig. 3. CO_2 equivalence factors (in kg/kg and kg/km) in dependency of flight altitude for several climate agents using atr_20 (left) and atr_50 (right) as uniform metric, respectively.

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emissions exceeding the emissions cap, emission permits have to be purchased by the airlines on the permits market. Most likely, emission permits will be bought from stationary sources because these emitters usually have much lower marginal abatement costs than aviation. The free allocation of permits leads to relatively low costs for complying with the trading schemes in the beginning of the timeframe analysed. In the course of time, the amount of emission permits which have to be purchased rises because aviation is expected to grow until 2030.

The costs for complying with the market-based measure under consideration have been quantified by multiplying the respective amount of CO_2 equivalent subject to the regulation scheme by the assumed prices for CO_2 equivalent, differentiated by the three price paths explained above. These costs will lead to a production cost increase of the airlines regulated. Under the modelling assumption that the airlines will try to pass-on the full cost increase to their customers, and will therefore act as profit maximizers, prices for air services will increase. How will demand for air services react to this price increase? In general, this demand reaction depends on the price elasticities of demand. As empirical data of the price elasticities of demand for air services show a broad range of possible figures (Oum et al., 1990, 1992; Lu, 2009), following three cases of price elasticities have been analysed alternatively:

- Case 1: Demand for air services reacts perfectly inelastic. In this case, the quantitative demand for air services remains unchanged.
- Case 2: Demand for air services reacts inelastic by a quantitative reduction of demand: A price elasticity of −0.8 has been assumed. The quantitative demand reaction is under proportionate to the price increase by the airlines.
- Case 3: Demand for air services reacts inelastic by a reduction of demand: A price elasticity of −2.1 has been assumed. The quantitative demand reaction is disproportionate to the price increase by the airlines.

This way, the complete range of possible demand side reactions can be analysed. In practice, we believe, case 2 may be the most likely reaction.

The demand reaction according to the cases 2 and 3 will have effects on the development of revenues of the airlines addressed by the climate protecting measure. In a next modelling step the airlines will change their flight plans (supply side effect) proportional to the change in demand. Implicitly, equality of demand and supply has been assumed here which is plausible after a certain adaption period. This will lead to a decrease in air traffic and a loss of employment in the aviation sector.

The employment effects have been quantified by using an Input–Output model. This model grounds on empirical Input–Output tables available for most countries in the world (see Eurostat, various years, for example). It allows for an estimation of the direct and indirect employment effect of the market-based measures investigated. This way, a comparative-static analysis of the employment effects has been conducted. The employment effects of the market-based measures investigated are presented and discussed in the AviClim full report (Scheelhaase et al., 2015).

The decrease in air traffic leads to a reduction in fuel used in our model. The reduction in fuel consumption has been estimated by VarMission (see section 'Models employed') on a flight-by-flight-basis. This results in a decrease of climate relevant emissions. Modal switching has not been considered in this study for simplification reasons. This will be subject to further research. Therefore, environmental benefits calculated are at the upper end and may be smaller in reality.

For both trading schemes (trading scheme for all climate relevant emissions and CO_2 trading scheme, respectively), additional CO_2 savings can be derived from the CO_2 purchases from other emitting sectors (e.g. stationary sources). These purchases are necessary to comply with the trading schemes as has been explained above.

The reduction in fuel consumption and the purchases of CO_2 permits will influence the temperature change induced by aviation, which has been estimated by employing the AirClim model (section 'Models employed').

AviClim's main results

The following graphs and explanations provide selected AviClim results in detail. At first, the cost impacts of the market-based measures analysed on the airlines are presented. As Fig. 4 illustrates, total costs for market-based measures regulating aviation's full climate impact will be the highest for a climate tax. In Scenario "Greater EU", which assumes a political support for these climate protecting measures in the European Union plus in Norway, Iceland and Liechtenstein, under the assumption of a moderate price development for CO_2 equivalent ('Low Price Path') and of the metric atr_50, total costs for the airlines will add up to 39 billion USD in 2030 at the most. In contrast, both an emissions trading scheme for all climate relevant emissions (solid line) and a NO_x charge combined with CO_2 trading and operational measures (dotted line) will lead to much lower overall costs: Total costs for an emissions trading scheme would amount up to 21 billion USD in the year 2030 and a NO_x charge combined with CO_2 trading and operational measures would add up to total costs of about 20 billion USD for all airlines addressed by the regulating measure. This can be explained by the specific assumptions set for both trading schemes analysed (trading scheme on all climate relevant emissions and CO_2-trading scheme which has been combined with the NO_x charge) as mentioned above: For the trading schemes a free allocation of 85% of 2010 emissions has been assumed, following the allocation rule of the EU ETS for aviation.

In the scenario "World" (Fig. 5), total costs for the three market-based measures investigated are much higher because in this scenario all airlines would be subject to the climate protecting measure under consideration. If the climate protecting

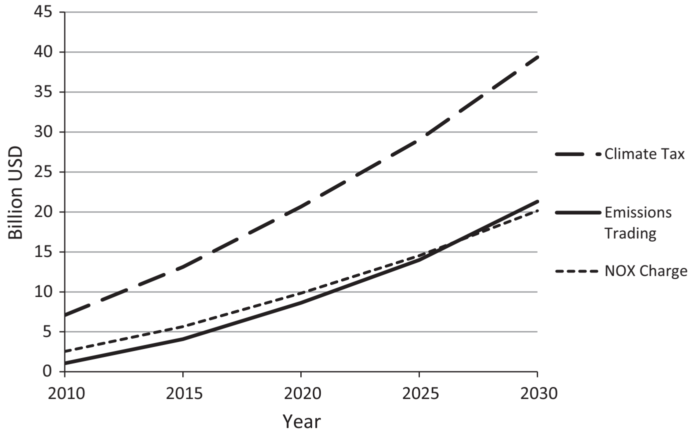

Fig. 4. Costs of different market-based measures analysed in Scenario "Greater EU", assuming the 'Low Price Path' and the metric atr_50. The costs are scaled to 2012 prices. The measure "NO_x Charge" includes CO_2 trading and operational measures (flying lower).

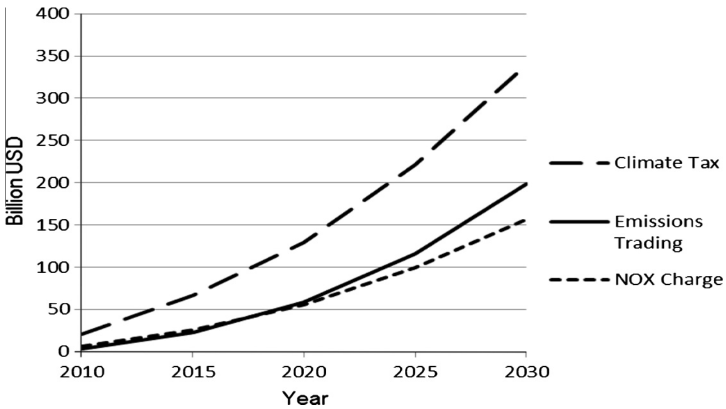

Fig. 5. Costs of different market-based measures analysed in Scenario "World", assuming the 'High Price Path' and the metric atr_50. The costs are scaled to 2012 prices. The measure "NO_x Charge" includes CO_2 trading and operational measures (flying lower).

measures were supported on a global level, total costs for a climate tax would add up to a nearly 340 billion USD in the year 2030 under the assumption of a high CO_2 equivalent price development path and the metric atr_50. Again, the total costs for an emissions trading scheme as well as for a NO_x charge combined with a CO_2 trading scheme and operational measures would be significantly lower: up to about 200 billion USD (emissions trading) and 156 billion USD (NO_x charge) in 2030, respectively.

The introduction of a market-based measure with an assumed price of 10 USD per ton CO_2 equivalent would lead to a cost increase of about 0.03 USD per kg jet fuel. Accordingly, a price of 30 USD per ton CO_2 equivalent would lead to a cost increase of about 0.10 USD per kg jet fuel. For comparison, 2013's jet fuel prices were about 0.9–1.0 USD per kg (IATA Platts, 2014).

An analysis of the specific costs (USD/RTK) shows a heterogeneous picture depending on market-based measure, the geopolitical scenario and Price Path assumed: For instance, the specific costs for airlines under the "Great Aviation Countries" scenario will increase by 0.230 USD per RTK on average (USD/RTK subject to the respective scenario) due to the climate tax in the year 2030 (High Price Path), while the specific costs for the airlines under the emissions trading scheme for all climate relevant species in the same year will increase by only 0.044 USD/RTK in the "Greater EU" scenario (Low Price Path).

Fig. 6 shows the large influence of the chosen metric on the results. In this figure, the total costs for the climate tax in the year 2030 for the four geopolitical scenarios investigated are presented with a moderate CO_2 equivalent price development ('Low Price Path'). Results for the metric atr_20 are marked in light grey, and results for atr_50 are marked in dark grey. Obviously, atr_20 leads to much higher costs than atr_50. This is because atr_20 weighs the effect of short-lived climate agents such as ozone and contrail cirrus stronger than atr_50, as short-lived climate agents show a large effect at the beginning of the time period analysed but a fast decrease in time, while CO_2 has a low impact at the beginning, but the effects only rather slowly decrease with time. If the resulting different total amounts of CO_2 equivalent are multiplied by the (same) prices for CO_2 equivalent, total costs for the climate tax will differ accordingly (Fig. 6).

Fig. 6 also reveals that the differences between the geopolitical scenarios "Great Aviation Countries" and "Annex-I-Countries" are rather small: For the 'Low Price Path' and the market-based measure climate tax, e.g., total costs

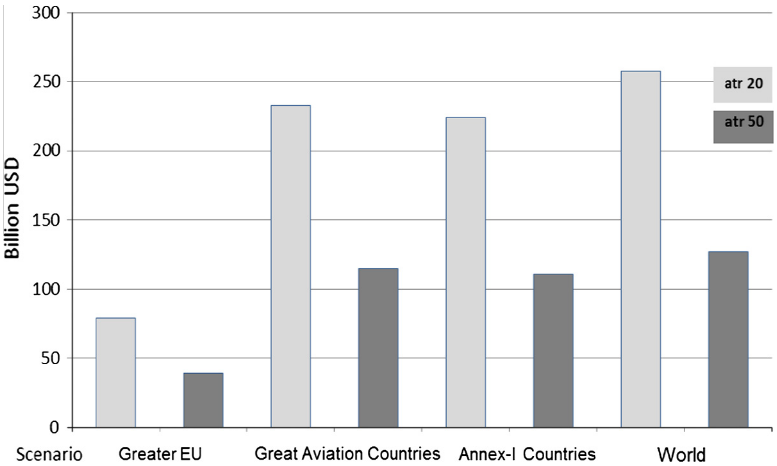

Fig. 6. Influence of the chosen metric on the costs for the climate tax in 2030 for different geopolitical scenarios. The 'Low Price Path' has been assumed here. The costs are scaled to 2012 prices.

of about 115 and 111 billion USD have been calculated for "Great Aviation Countries" and "Annex-I-Countries", respectively, in the year 2030. This can be explained by the fact that the Annex-I Countries plus the BRIC States are mostly congruent with the "Great Aviation Countries". Not surprisingly, total costs calculated for the geopolitical scenario "World" are the highest, about 10% more than for the "Great Aviation Countries". This is true for all climate protecting instruments analysed. For the 'High Price Path' and atr_50, for instance, total costs range from 156 to 339 billion USD (NO_x charge and climate tax, respectively) in 2030.

In a next modelling step we calculated how the costs for the market-based measures will increase the production costs of the airlines regulated. Under the assumption that the airlines will act as profit maximizers as mentioned above, prices for air services will increase. The demand reaction according to the price elasticity cases 2 and 3 explained above will have effects on the revenues of the airlines under the climate protecting measure. Modelling results show that under the assumption of a price elasticity of demand of -0.8 (case 2), revenues will still be increasing steadily in the period 2020–2030, even though on a lower stage than in the business-as-usual development. This is true for all metrics and price paths assumed. The same applies to a demand reaction according to case 3 and the 'Low Price Path'. These effects are shown in Fig. 7, which presents selected demand side effects for the 'High Price Path' and the metric atr_50.

In contrast, under the assumptions of the metric atr_20, a demand reaction according to case 3, and the 'High Price Path', airlines' revenues will be shrinking drastically. If demand for air services will react to the high price increase by a disproportionate demand reduction, this will lead to strongly negative effects for the airlines under the climate protecting measure. Under these assumptions, the disproportionate demand reaction and the high CO_2 equivalent prices are interacting in an unfavourable way. This applies to all climate protecting measures investigated.

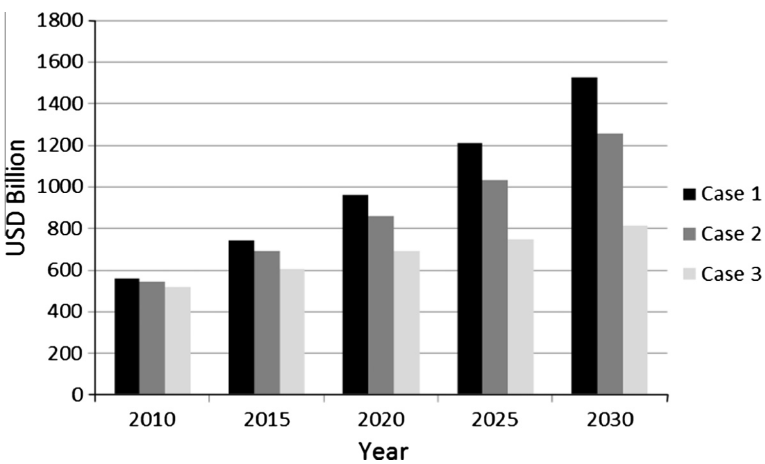

Fig. 7. Demand side effects of the Climate Tax in Scenario "World" differentiated by alternative price elasticities of demand (cases 1–3). The 'High Price Path' and the metric atr_50 are assumed here. The costs are scaled to 2012 prices. Case 1 is identical to the Business-as-usual development.

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Fig. 8 shows the development of air traffic in the scenario ''Great Aviation Countries'' for atr_50 and the 'Low Price Path'. Here, a demand reaction according to case 2 has been assumed. Air traffic will be affected by the three market-based measures analysed in the range of minus 0.5% to minus 7% of Revenue Ton Kilometres (RTKs) in the period from 2010 to 2030. Again, effects of the climate tax are the largest while the impacts of the emissions trading scheme for all climate relevant emissions and the effects of the NO_x charge combined with CO_2 trading and operational measures are lower by far.

The reduction in air traffic leads to a reduction of climate relevant emissions from aviation in our model since less fuel will be burned and also the non-CO_2 climate effects such as contrails are reduced. Table 1 provides an overview of the change in fuel consumption calculated for the different reduction measures in the year 2030 for the metric atr_50 and case 2 demand reaction. For the two market-based measures analysed, which include emissions trading, additional environmental benefits are derived from the necessary purchase of CO_2 allowances from other sectors. This is because under an emissions trading scheme, the airlines can purchase emission allowances from other sectors (such as stationary energy plants or energy-intensive industries) in order to comply with the regulation scheme.

Fig. 9 presents the impact of the reduced air traffic on climate in terms of CO_2 equivalents for the 'Low Price Path' and the geopolitical scenario ''Great Aviation Countries''. Although the air traffic reduction is the largest for the climate tax, the climate impact of the climate tax is lower than the effects calculated for the market-based measures 'emissions trading for all climate relevant species' and 'NO_x charge combined with CO_2 trading and operational measures'. This is due to the fact that under both trading schemes purchases of CO_2 permits from stationary sources also have been attributed to the environmental effects.

On what terms can these purchases of CO_2 permits from stationary sources be attributed to aviation's climate relevant savings? This attribution can only be made if aviation's demand on the market for CO_2 permits provides incentives for additional CO_2 reductions in other emitting sectors and additional supply of these permits will be created. Given the relatively high marginal abatement costs of aviation, it seems reasonable to believe that airlines will be willing to pay higher prices for CO_2 permits than most other emitting sectors. Against this background it is plausible that aviation's purchases on the CO_2 permits market will result in additional CO_2 savings of other emitters. On these conditions aviation's CO_2 purchases on the CO_2 permits market have been attributed to aviation's climate relevant savings.

The temporal development of climate impact in terms of temperature change is presented in Fig. 10 for the two extreme cases: the geopolitical scenario ''Greater EU'' with the 'Low Price Path' versus the geopolitical scenario ''World'' with the 'High Price Path'. For the scenario ''Greater EU'' with the 'Low Price Path', but without the possibility to buy permits from other sectors, only small impacts on the temperature change can be realized, as only a small part of global aviation is

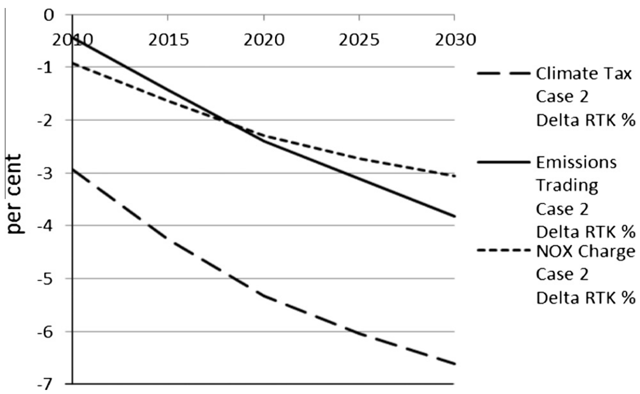

Fig. 8. Change of air traffic in per cent relative to Business-as-usual. The scenarios ''Great Aviation Countries'', the metric atr_50, the 'Low Price Path', and the price elasticity ''case 2'' have been assumed here.

Table 1
Change in fuel consumption compared to Business-as-usual in the year 2030 for the case 2 demand reaction and the metric atr_50. NO_x charge includes CO_2 trading and operational measures.

	''Greater EU'' (%)	''Great Aviation Countries'' (%)	''World'' (%)
Low price scenario			
Climate tax	−1.8	−5.9	−6.7
Emissions trading	−0.9	−3.4	−3.9
NO*x* charge	−0.6	−1.9	−2.2
High price scenario			
Climate tax	−5.1	−15.8	−17.8
Emissions trading	−2.7	−9.2	−10.4
NO*x* charge	−2.4	−6.5	−7.4

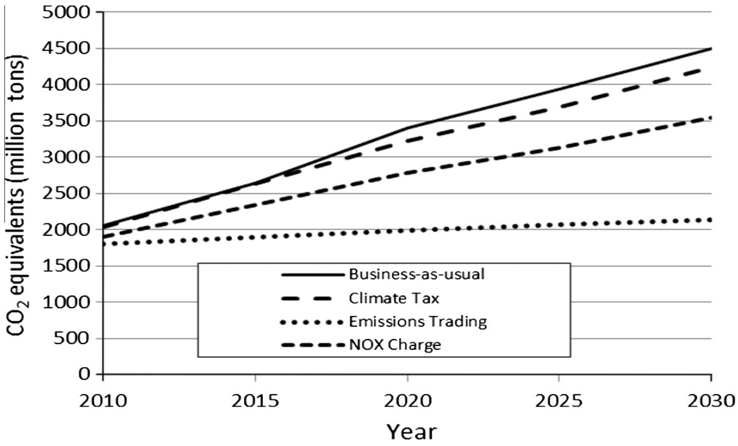

Fig. 9. Climate impact in terms of CO_2 equivalents for different market-based measures including CO_2 purchases for the geopolitical scenario "Great Aviation Countries". The 'Low Price Path' and the metric atr_50 have been assumed here.

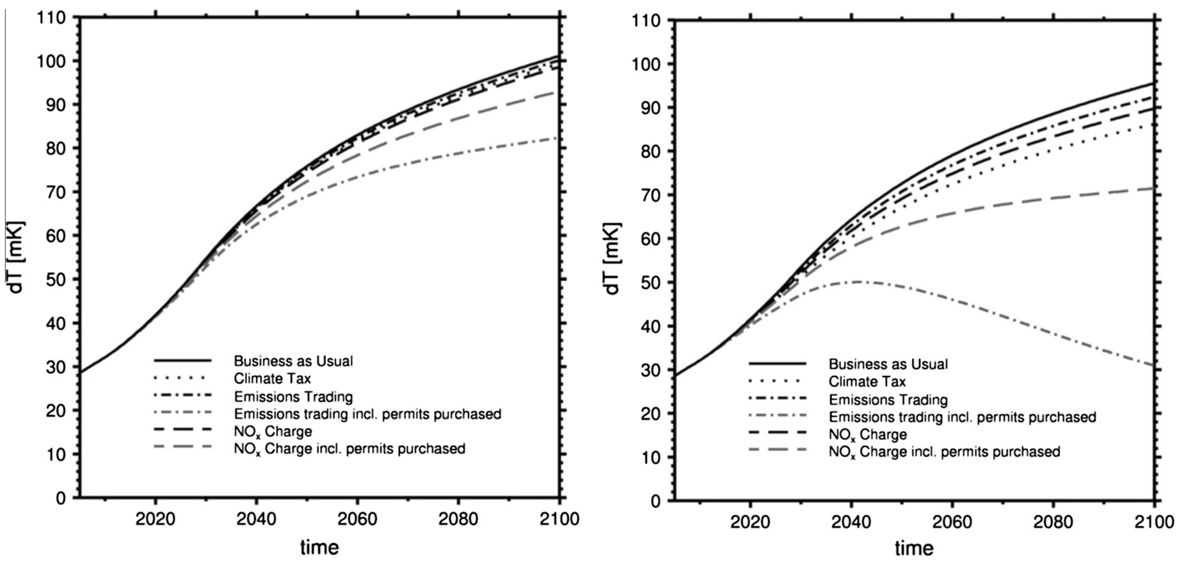

Fig. 10. Temporal development of temperature change for the scenario "Greater EU" with the 'Low Price Path' (left panel) and the scenario "World" with the 'High Price Path' (right panel). The Business-as-usual scenario is plotted for comparison.

influenced by this scenario. If purchases of permits are taken into consideration, the temperature change in the year 2100 will be reduced by about 18% for the market-based measure emissions trading. If the whole world is supporting this climate political measure, the temperature change will be reduced by 15% compared to the Business-as-usual (BaU) scenario without purchases. If purchases are taken into account, the temperature change is reduced by up to 70% in the year 2100. Due to the fact that for emissions trading the amount of purchases from other sectors is larger than the CO_2 emission from aviation, the temperature change decreases after 2040 despite constant aviation emission after 2030. The increasing temperature change after 2030 for all other scenarios is due to the thermal inertia of the atmosphere and due to the fact that CO_2 has a very long lifetime and accumulates in the atmosphere. Overall, AviClim results show that environmental benefits are the greatest for the emissions trading scheme for all climate relevant emissions from aviation.

Fig. 11 presents an overview of the relative climate impact reduction potential for the different market-based measures, geopolitical scenarios and price paths analysed. The largest reduction potential is provided by a global emissions trading scheme taking purchases of emission permits into account and a 'High Price Path' (about 40%). The difference between the reduction potential of about 40% shown in Fig. 11 and the 70% shown before is caused by the metric used. If only the temperature change in the year 2100 is taken into account, the impact of the reduced CO_2 emissions plays a more important role, as those emissions would otherwise accumulate in the atmosphere and lead to a large temperature increase. Analysing the climate impact of the metric atr_50, the impact of the short-term climate agents ozone and contrail cirrus dominates, leading to a smaller impact of the reduced CO_2 emission.

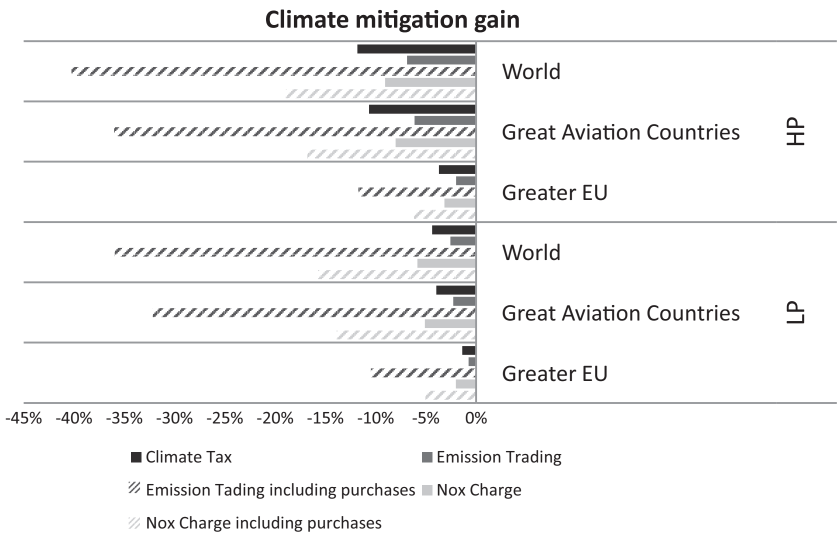

Fig. 11. Overview of the relative change in climate impact in terms of atr_50 due to different market-based measures for alternative geopolitical scenarios and price paths (HP = 'High Price Path', LP = 'Low Price Path').

Summary and recommendations

The AviClim study presents a promising beginning towards understanding the options for including the full climate impact of aviation in international protocols for climate protection. AviClim provides insights on the economic and environmental impact, the economic efficiency and the consistency of the investigated market-based and operational measures for the reduction of the non-CO_2 impact of aviation. By analysing four different geopolitical scenarios of international support for climate protecting measures in aviation, three alternative market-based measures, three price paths for CO_2 equivalents and three basic demand reaction cases, a large spread of options has been investigated both from an economic and from an environmental point of view.

Results show that a global emissions trading scheme for the political regulation of both CO_2 and non-CO_2 emissions of aviation under the assumptions explained above would be the best solution from an economic and environmental point of view. Costs and impacts on competition could be kept at a relatively moderate level. At the same time, environmental benefits are significant. For instance, under the assumption of the 'High Price Path' the temperature change induced by aviation could be reduced by up to 70% in the year 2100 compared to the business-as-usual development assuming constant emission after 2030.

For this positive environmental outcome, aviation's purchases of CO_2 permits from stationary sources are very important. On what terms can these purchases of CO_2 permits be attributed to aviation's climate relevant savings? This attribution can only be made if aviation's demand on the market for CO_2 permits provides incentives for additional CO_2 reductions in other emitting sectors and additional supply of these permits will be created. Given the relatively high marginal abatement costs of aviation, it seems reasonable to believe that airlines will be willing to pay higher prices for CO_2 permits than most other emitting sectors. Against this background it is plausible that aviation's purchases on the CO_2 permits market will result in additional CO_2 savings of other emitters. On these conditions aviation's CO_2 purchases on the CO_2 permits market have been attributed to aviation's climate relevant savings.

As modelling results for the geopolitical scenarios "Great Aviation Countries" and "Annex-I Countries" have shown, the environmental and climate protecting benefits gained here are almost at the level of a global solution. This is because in these geopolitical scenarios more than 90 per cent of the global flights would be regulated by the climate protecting measure under consideration. This expectable result provides insights for the discussions on ICAO level: Depending on the actual national and international support for climate protecting measures, a political solution for the "Great Aviation Countries" or the "Annex-I Countries" could possibly be easier to find than for a global scheme. As negotiations in the past have shown, in particular some developing countries responsible for very small amounts of climate relevant emissions have been blocking global solutions. This leads to the conclusion that it would be advantageous to get started soon with a limited number of countries supporting climate protecting measures in aviation than to wait for a worldwide agreement. To minimize competitive distortions, the countries of origin of the main players in aviation should be included from the beginning.

The second best solution with regard to the market-based measure chosen would be the combination of a NO_x charge with CO_2 trading and (simple) operational measures. These political measures will allow for environmental and climate protecting benefits just below the benefits gained by the emissions trading scheme for all climate relevant species from aviation as AviClim modelling results have demonstrated. A possible disadvantage of such a combination of market-based and operational measures could be higher transaction costs on the governmental as well as on the airlines level. This is due to the fact that it will be more complicated to implement, handle and monitor three different regulatory approaches than one single solution.

On the basis of the 38th ICAO Assembly Resolution (ICAO, 2013b) the discussion on ICAO level currently concentrates on the design of offsetting schemes for the limitation of international aviation's CO_2 emissions. Offsetting is a variant of emissions trading with some differences to the emissions trading scheme analysed within AviClim. As mentioned above, the implementation of such an offsetting scheme is envisaged for the year 2020. It remains to be seen whether ICAO will be successful within this timeframe as discussions are difficult as it is the case with many UN agencies and institutions. If ICAO negotiations will succeed, AviClim results could be used to expand the CO_2 scheme to the non-CO_2 climate relevant species from aviation as a next step. Here, both the extension of the CO_2 offsetting scheme to other climate relevant species and the introduction of operational measures such as climate optimal flight trajectories could be worthwhile considering.

Therefore, this study is a step towards developing climate-protecting measures addressing the full climate impact of aviation. Future efforts are headed towards extending the AviClim model to biofuels, a larger use of climate-optimal operational measures and to investigate the effects of modal switching. This would be of interest in order to improve the model and to investigate aviation's possibilities to abate climate relevant emissions in the medium term.

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