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LETTER

Feasibility of climate-optimized air traffic routing for trans-Atlantic flights

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Abstract

Current air traffic routing is motivated by minimizing economic costs, such as fuel use. In addition to the climate impact of CO_2 emissions from this fuel use, aviation contributes to climate change through non-CO_2 impacts, such as changes in atmospheric ozone and methane concentrations and formation of contrail-cirrus. These non-CO_2 impacts depend significantly on where and when the aviation emissions occur. The climate impact of aviation could be reduced if flights were routed to avoid regions where emissions have the largest impact. Here, we present the first results where a climate-optimized routing strategy is simulated for all trans-Atlantic flights on 5 winter and 3 summer days, which are typical of representative winter and summer North Atlantic weather patterns. The optimization separately considers eastbound and westbound flights, and accounts for the effects of wind on the flight routes, and takes safety aspects into account. For all days considered, we find multiple feasible combinations of flight routes which have a smaller overall climate impact than the scenario which minimizes economic cost. We find that even small changes in routing, which increase the operating costs (mainly fuel) by only 1% lead to considerable reductions in climate impact of 10%. This cost increase could be compensated by market-based measures, if costs for non-CO_2 climate impacts were included. Our methodology is a starting point for climate-optimized flight planning, which could also be applied globally. Although there are challenges to implementing such a system, we present a road map with the steps to overcome these.

1. Introduction

The impact of aviation on climate, i.e. the impact on global mean near-surface air temperature, has been summarized in assessment reports (IPCC 1999, Lee *et al* 2010, Brasseur *et al* 2016). Roughly 5% of anthropogenic climate change is attributed to global aviation (Skeie *et al* 2009, Lee *et al* 2010) and this number is expected to grow further. A wide range of atmospheric processes determine the impact of aviation emissions on climate, which include advection, dispersion, wash-out, chemical conversion, cloud formation (contrail-cirrus), and solar and infrared radiation. In addition to aircraft emissions of carbon dioxide, emissions of water vapor and nitrogen oxide-and potentially also particulates—contribute to the climate impact. Contrails only form when the mixture of the hot and moist exhaust with the ambient air becomes saturated with respect to water and only persist if the ambient air is saturated with respect to ice. Contrails influence both the budget of incoming solar radiation and the outgoing infrared radiation emitted by the Earth and its atmosphere—on average, contrails act to warm the climate, but in certain circumstances (e.g. close to sunrise and sunset) the reverse can be true (Meerkötter *et al* 1999, Myhre and Stordal 2001). The effect of perturbations on the energy balance are quantified using the radiation imbalance at the tropopause (radiative forcing, RF) (IPCC 2013). Positive RF will lead to warming and vice versa.

Nitric oxide (NO) reacts with hydroperoxyl (HO_2) forming a hydroxyl radical (OH) and nitrogen dioxide (NO_2). This initiates two other mechanisms, the production of ozone via the photolysis of the NO_2 molecule, forming an oxygen atom, which recombines with oxygen to form ozone and the reaction of the hydroxyl radical with methane. Hence the emissions of nitrogen oxides lead to an enhancement of ozone and a decrease in methane concentrations (which itself leads to a reduction in the ozone production). Both ozone and methane are greenhouse gases and changes in their concentrations cause RF.

The warming from increases in ozone dominates over the cooling due to methane decreases for the current global fleet (Lee *et al* 2010). However, locally the net effect can vary significantly (Köhler *et al* 2008, Stevenson and Derwent 2009) and NO_x emissions in some regions can lead to a global cooling (Grewe and Stenke 2008). Similarly, contrail formation, properties and the related climate impact vary significantly between different regions and times (Ponater *et al* 2002, Marquart *et al* 2003, Palikonda *et al* 2005, Meyer *et al* 2007, Myhre and Stordal 2001). Hence the climate impact of these non-CO_2 emissions depends strongly on the altitude, geographic location and time of the emission referring to the diurnal as well as the seasonal cycle (e.g. Fichter *et al* 2005, Mannstein *et al* 2005, Meerkötter *et al* 1999, Gauss *et al* 2006, Grewe and Stenke 2008, Frömming *et al* 2012).

The climate impact of aviation could potentially be reduced if flights were routed to avoid regions where emissions have the largest impact (Sausen *et al* 1994; Schumann *et al* 2011, Sridhar *et al* 2011, Gierens *et al* 2008, Grewe *et al* 2014b). Here, we investigate whether the introduction of a reduced climate impact routing strategy is beneficial for climate change. The objective of our study is to show the feasibility of such a routing strategy by taking into account a representative set of weather situations for winter and summer seasons and optimizing all trans-Atlantic air traffic on those days and taking safety issues fully into account. An overview of the calculation of the climate-optimal routes, climate metrics and air traffic simulation is given in section 2. The impact of the climate-optimized routing strategy on climate impact and cost is presented in section 3, as well as a consideration of the use of market-based measures to incentivise the use of such a strategy, and a roadmap for implementation. Uncertainties and a comparison to previous work are discussed in section 4.

2. Methods

2.1. Overview

To examine the relationship between changes in the climate impact and changes in costs for routing options, we apply a four step procedure. First, for each case study day, radiative forcings resulting from locally-confined unit emissions over the north Atlantic are calculated (section 2.2) by employing the detailed chemistry-climate model EMAC (Jöckel *et al* 2010, 2016) and then globally averaged. Second, the climate change induced by these emissions is calculated by applying emission metrics to these RF, resulting in climate-change functions (section 2.3, referred to in previous publications as climate-cost functions). The emissions represent a change in the routing strategy towards climate-optimized routing. Third, these CCFs are input to an air traffic simulator (section 2.4). For each flight lateral and vertical variations in the flight profile are considered, resulting in a number of possible flight paths for each flight. The climate impact of each possible flight path of the roughly 800 trans-Atlantic flights (figure 1) is calculated from the CCFs; in addition the cost of each flight is also considered. Finally, for this large set of possible traffic realizations, the optimal relation between climate impact reduction and cost increase relative to the minimum cost situation is derived by successively replacing the flight trajectories with the highest ratio of climate impact reduction versus costs increase. Details of the underlying methodology have been reported previously (Grewe *et al* 2014a) as have results for one individual case study day in winter (Grewe *et al* 2014b).

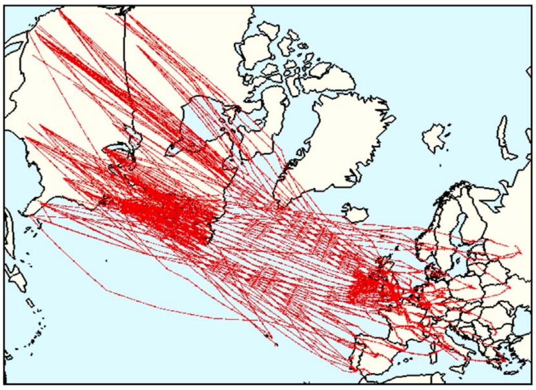

Figure 1. Actual flight paths for all trans-Atlantic flights on one day, which corresponds to the first winter weather pattern (WP1). These roughly 800 flights are modified for climate-optimal routing.

2.2. Atmospheric changes and radiative forcing

The climate impact of local emissions, i.e. the climate-change functions, are determined for five winter and three summer days, which represent frequently-occurring North-Atlantic winter and summer weather patterns (WP and SP) using the classification of Irvine *et al* (2013). They are classified by their similarity to the North Atlantic Oscillation and East Atlantic teleconnection patterns, which describe main circulation patterns and impact the location and strength of the jet stream. For example WP1 is characterized by a strong zonal jet stream, whereas WP3 is a blocking situation. Winter weather patterns 1–4 each occur on average between 16%–18% of the time, whereas WP5 has the highest frequency of occurrence of 26%. The summer pattern 2 (SP2) is most frequently occurring weather pattern during summer with 60% of the time and SP1 and 3 occurring each 20% of the time.

For each weather pattern, one day was selected, which best represents the location and strength of the jet stream of that weather pattern. For each of these days, unit amounts of nitrogen oxide, water vapor, and carbon dioxide are released at about 500 different points in the atmosphere. At each of these 500 points 50 air parcels are started in which chemical perturbations are calculated. In addition, a flight distance is accounted for in every air parcel to simulate the effect of contrails. These emission points are located in an area over the north Atlantic, at multiple levels which cover the main North Atlantic flight levels, and the unit emissions occur at multiple times during the day. The processes simulated in the air parcels include effects from emissions of CO_2, H_2O, NO_x, and the formation of contrail-cirrus. Emitted nitrogen oxides are converted to HNO_3, which is rained out depending on the simulated cloud physics. HNO_3 can also be reconverted into NO_x. The nitrogen oxides concentration in the air parcel further affect ozone production via the reaction of $NO+HO_2 \rightarrow NO_2 + OH$, where NO_2 easily photolyses and the resulting O atom recombines with molecular oxygen (O_2) to form ozone. In addition the emitted NO_x impacts the OH to HO_2 ratio in favor of OH (see reaction above). The latter is important since the increased OH reduces the background methane concentration. The same effect also results from the produced ozone, which is destroyed by photolysis. The resulting atomic oxygen reacts with water vapor to form OH, which again leads to methane loss. Water vapor is, in a similar way to NO_x, emitted into the air parcels, which are transported with the winds in the atmosphere. Whenever precipitation occurs, the water vapor in the air parcels is rained out. Contrails form within the air parcels whenever the Schmidt-Appleman criterion is fulfilled. They are persistent if the air is saturated with respect to ice. Persistent contrails increase the cirrus coverage and, depending on the available water vapor and the prevailing temperature, the contrail coverage and contrail ice water content can grow due to water vapor uptake or shrink due to sublimation. Contrail ice particles sediment and sublimate whenever the air parcel is transported to warmer atmospheric layers. Wind shear acts on the contrails and results in a spreading of the contrail and hence increases the contrail coverage. The contrail coverage, however, is limited by the potential contrail coverage, which is the fraction of an EMAC grid box, which can maximally be covered by contrails. All regarded quantities are transformed from the air parcels onto the EMAC grid, where radiation changes are calculated, and then globally averaged. The resulting changes in the concentrations of—and RF from—CO_2, ozone, methane, water vapor and contrail-cirrus then provide the relationship between a local emission and the resulting global-average RF. Further details of this modelling approach are reported in Grewe *et al* (2014a).

The simulation of chemical and contrail effects were validated in Grewe *et al* (2014a) by analyzing key parameters: The temporal course of the response of nitrogen oxide, ozone and methane to an initial unit emission agrees well with results from Stevenson *et al* (2004). The frequency distribution of ice water content of the simulated contrails agrees well with results from *in situ* measurements by Voigt *et al* (2011), whereas the frequency of optically thin (with respect to the visible spectral range) contrails is larger in our simulation. The specific radiative forcing of contrails has been verified with the Myhre *et al* (2009) benchmark test, which determines the RF for a 1% cirrus increase at 11 km with an optical depth of 0.3. The results fall well within the range of other model results.

2.3. Climate metrics and climate-change functions

To choose an appropriate climate metric we pose the question, what potential reduction in climate impact could be achieved by steadily applying a climate optimizing aircraft routing strategy, especially in the next few decades? From this objective we derive an adequate climate metric (Grewe and Dahlmann 2015). We consider a business-as-usual future air traffic scenario as a reference and compare that to a scenario where we daily fly trans-Atlantic routings with a low climate impact. We use the global and temporal average near-surface temperature response over 20 years after introducing the climate-optimized routing strategy. This metric enables the different climate relevant emissions to be placed on a common scale and thus be directly compared. Other metrics, which are suitable to assess a continuous change in the routing strategy, were investigated without significantly altering the conclusions (Grewe *et al* 2014b). We note that had we adopted the more frequently used pulse-based metrics (e.g. Fuglestvedt *et al* 2010), we would have found much stronger sensitivity, and more contrast between the short- and long-lived emissions—however, these would not have been best suited to quantifying the sustained impact of a permanent change in routing strategy on near-term climate change, which is the aim here. Applying this metric to the calculated RF (section 2.2) we then obtain a relation between locally and temporarily specified emissions and the global-average impact on climate in terms of future temperature changes. We call these 4-D response patterns 'climate-change functions' (CCFs). They comprise, e.g. the contribution from NO_x emissions to the global-mean climate impact via ozone. The climate impact of NO_x emissions depends significantly on where they are emitted

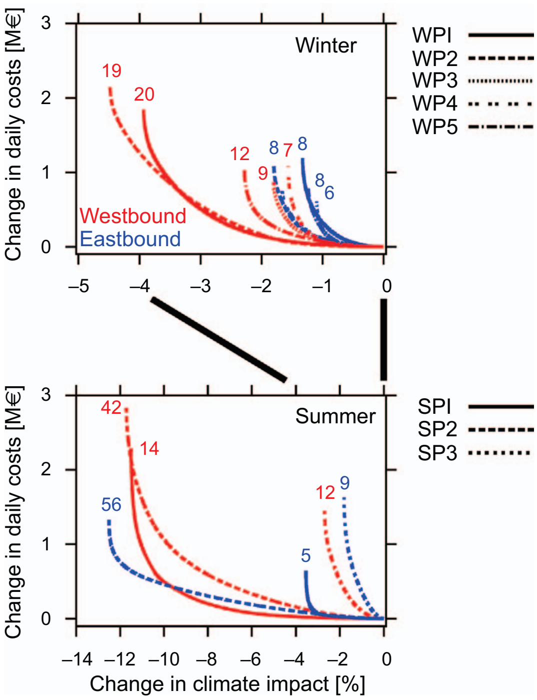

Figure 2. Optimal climate-cost relations for one day of trans-Atlantic air traffic (see figure 1) for 5 representative winter (top) and 3 summer (bottom) days. The set of trans-Atlantic aircraft trajectories, which has minimum operational costs, is taken as the reference, i.e. the point of origin. Note that the top and bottom figures have different ranges for the climate impact reduction. See text for details of the meaning of the numbers at the end of each curve.

with higher impacts for emissions in the jet stream and lower values for emissions north of it (Grewe *et al* 2014b).

2.4. Air traffic simulation

The CCFs are included in a state-of-the-art air traffic simulator (SAAM, Eurocontrol 2012). We evaluate 85 alternative routings (17 horizontal and 5 vertical) for each of the roughly 400 flights crossing the North Atlantic in either direction each day with respect to climate impact and costs (figure 1). This simulator includes wind effects on flight trajectories. Additionally necessary safety margins in terms of separation of individual flights are taken into account. The traffic simulation provides a huge number of flight combinations, each forming a set of around 800 flights. We calculate an optimal relation between climate impact reduction and cost increase (figure 2). Starting point for this calculation is the set of flight trajectories, which minimizes costs (lower right). Here we consider fuel and crew costs. Then we calculate for every alternative flight trajectory the ratio between climate impact reduction and cost increase and pick that with the largest ratio, i.e. the most eco-efficient trajectory change. This procedure is repeated as long as we arrive in the climate optimal situation (upper left). The costs (M€), presented here, refer to one day of operation and the climate impact reduction refers to mean temperature change over the next 20 years for a change in the routing strategy towards a climate impact reduction, relative to the mean temperature change from aviation of all summer and winter situations (weighted with their frequency of occurrence).

To account for safety issues 4 further optimizations were performed along the line of optimal relations between climate impact reduction and cost increases, which include a separation of aircraft following standard safety margins. The results hardly differ, showing that over the Atlantic air traffic density is not a limiting factor for climate-optimized routing (Grewe *et al* 2014b). But it may well be, that climate optimized routing and safety would be in conflict over more congested areas like Europe and north-east of the USA.

3. Results

3.1. Climate impact reduced routing and impacts on costs

From the large set of possible combinations of flight options, the minimum cost and minimum climate impact combinations are derived as are the most cost-effective intermediate solutions (figure 2). Costs and climate impacts are presented with respect to the emissions from one day. Optimal climate-cost relations are then obtained by successively changing individual aircraft trajectories, which have the highest ratio of climate impact reduction to costs. This reduces the climate impact of the whole one day trans-Atlantic air traffic and increases the costs. Westbound (red) and eastbound (blue) climate-cost relations are given separately, because the tailwinds have a large impact on routings and hence on these relations. Numbers at the endpoint of each curve indicate the climate impact reduction (%) relative to the climate impact of aviation flown at minimum costs, separately for each weather pattern and flight direction (rather than relative to all summer and winter situations and both flight directions, as given on the x-axis); thus, a saving for an individual pattern may be high, but if that pattern occurs less frequently, it contributes less to the total gain.The daily maximum climate impact reduction for a specific weather pattern ranges between 5% and 56% compared to the climate impact of the fleet of aircraft flown at minimum economic costs in that respective weather pattern and flight direction. These reductions are associated with increases in costs ranging from 0.6 M€ to 2.8 M€ per day, which is around 3.5% to 11%, depending on the weather situation. Note that the climate impact of an individual flight is almost negligible. However, if these climate impact reductions were achieved every day the total climate impact of air traffic could be reduced significantly. A clear difference in the climate-cost relations between westbound and eastbound air traffic is found between the winter patterns WP1 and WP2 and the other patterns. WP1 and WP2 are

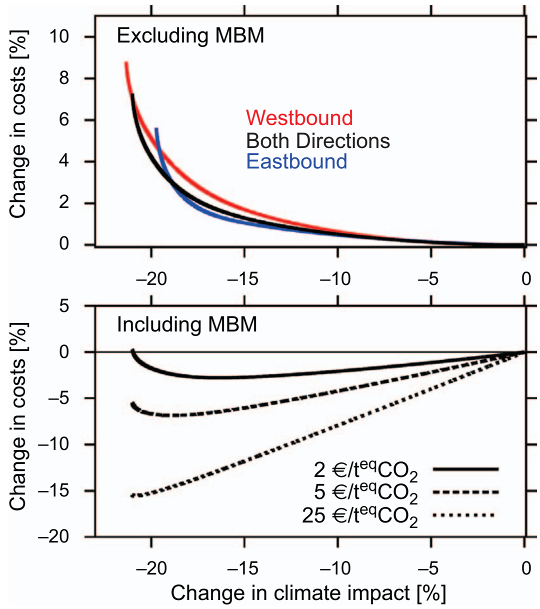

Figure 3. Top: same as figure 2 but averaged over the climatological frequency of all weather situations. West- and eastbound traffic is given relative to the climate impact of aviation flown west- and eastbound at minimum costs, respectively. Bottom: inclusion of costs for non-CO_2 effects through market-based measures, in addition to the operational costs.

characterized by a strong zonal jet stream. The eastbound traffic takes advantage of tailwinds within the jet stream. Leaving the jet stream implies large penalties on fuel demand, emissions and climate impact; hence eastbound winter flights show less potential to reduce climate impact. By contrast, for WP4, an intense blocking situation, where the direction of the jet stream is more northward or southward, the difference between east- and westbound traffic is smaller. The summer patterns show a larger variability and a larger potential to reduce the climate impact from aviation by climate-optimized routing. The weather situation SP1 with a fairly zonal jet stream is similar to WP1 and shows a large difference between the flight directions, also similar to WP1.

Most of the potential climate impact reductions can be achieved at relatively low additional costs resulting in a 10% decrease in climate impact for only a 1% cost increase when all weather situations with their climatological frequency of occurrence are taken into account (figure 3, top). The maximum climate impact reductions are around 20% and relate to the maximum climate impact reductions shown in figure 2 by adding the weighted averages of the winter and summer values and adding the results for both flight directions. This cost efficient reduction in the climate impact is mostly achieved by avoiding the formation of warming contrails and by producing cooling contrails. However, it is also important to include the effect from NO_x emissions, since they often counteract the climate gain from the contrails (Grewe *et al* 2014b).

3.2. Market-based measures

Such cost increases in the order of 1% may not be acceptable to aviation stakeholders. Overall operational cost is the principal driver for routing strategies. Under the current regulations there is no incentive to fly routes that minimize the total climate impact of CO_2 and non-CO_2 emissions. However, if a market-based measure were in place, which included the climate impact of contrail formation and NO_x-emissions, airlines would have an incentive to fly routes that minimize the total climate impact. Here, we use the total 'equivalent CO_2 emissions (eq. CO_2)' which is the amount of CO_2 that would produce the same averaged temperature response as the combination of CO_2 and non-CO_2 emissions over the 20 year period. We add the costs for CO_2 (currently ∽5–10 € per ton) to the operating costs (figure 3, bottom) and also consider an upper and lower limit of 2 and 25 € per ton of eq. CO_2 emission, respectively. Reducing the climate impact by climate-optimized routing implies that lower eq. CO_2 costs are incurred, which reduces the operational costs. This results in a roughly 10% decrease in climate impact and a decrease of the cash operating costs by 5% for the trans-Atlantic air traffic.

3.3. Roadmap

Our results clearly show that under appropriate framework conditions and regulations, cost-effective climate-optimized routing has the potential to significantly reduce the climate impact from aviation. However, our study also raises questions and potential concerns, regarding the maturity level, scientific uncertainties, and also political and ethical questions. Clearly, our approach needs further development, for which we have formulated a road map (figure 4), before it can be used operationally. It includes systematic studies between the climate-change functions and weather systems to derive relationships between weather forecasts and the climate impact of a local emission. These algorithm-based CCFs and the climate impact reduction would need to be tested and verified. A feasible self-consistent way is to implement an air traffic simulator in an Earth-System Model and to optimize the climate reduction within this model (Yamashita *et al* 2016).

Here, we concentrated on one specific region and showed that under current regulations safe climate—optimized routing is feasible. More studies are required to investigate the feasibility of climate beneficial routing and the impact on ATM over areas like Europe or America with a much larger traffic density.

4. Discussion

4.1. Sources of uncertainties

The CCFs have to be mature enough to be used operationally. For example, we do know under which conditions contrails form (Schmidt 1941,

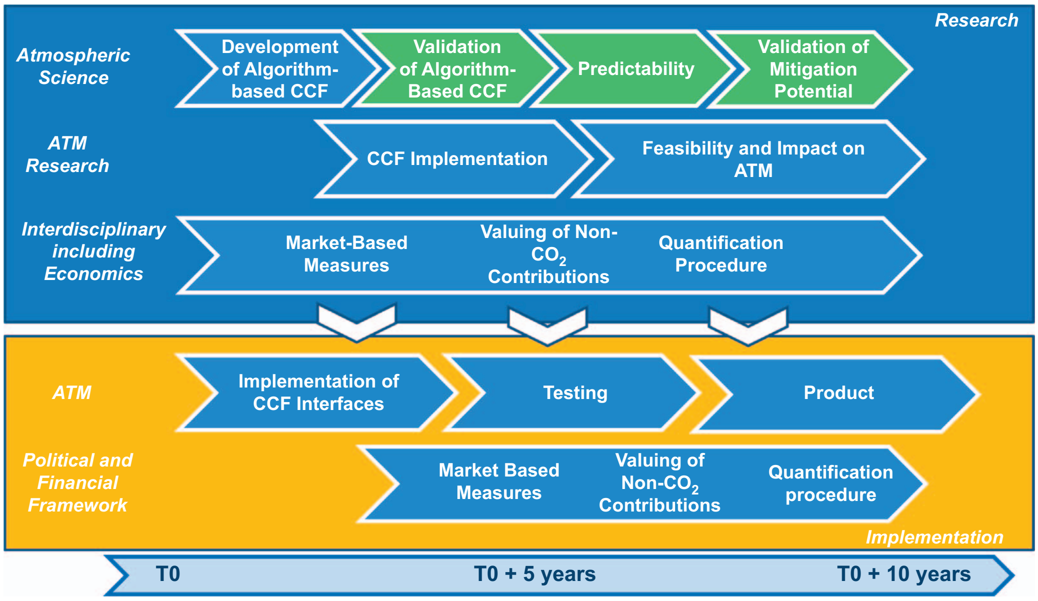

Figure 4. Road map for implementing climate-optimized routing. Research and implementation activities are indicated in the blue and orange box, respectively. Validation activities are marked in green.

Schumann 2000). But, are we able to predict the locations which support the formation of persistent contrails with sufficient accuracy? Even predicting those regions is not sufficient to determine the climate impact of contrails. This is because interactions between (micro-) physical processes, such as transport, dispersion, sedimentation, growth of particles, shape of contrail ice particles and their impact on radiation are important in determining the contrail RF values. The large atmospheric variability impacts these interactions and leads to large RF ranges. In addition, aircraft and especially fuel characteristics influence the contrail RF. For instance, the number of ice crystals formed initially is a strong function of the number of soot particles emitted (Kärcher and Yu 2009). Condensation of water vapor on soot surfaces proceeds on certain chemical compounds, so-called functional groups which due to their polarity can attach water molecules. Water soluble substances on the soot surfaces can greatly enhance absorption of water vapor. Sulfur can contribute to both the functional groups and the water soluble material, but according to laboratory studies (Popovicheva *et al* 2004, 2008, Demirdjian *et al* 2007) it is not the main constituent. Thus, we think, if sulfur-free fuel is burned, contrail formation will largely be unaffected.

In a case study we have analyzed the sensitivity of the cost-benefit analysis and related air traffic responses with respect to potential errors in the climate-change functions (Grewe *et al* 2014b). For example, we changed the weighting between the climate impact from NO_x and contrail-cirrus. In this case, the air traffic system still behaves similarly during the optimization. These sensitivity studies indicate a stable response in the shape of the cost benefit analyses and the way air traffic is routed for climate impact reduction. There are other non-CO_2 impacts not included in our present study, as they are much more uncertain, for example, the effect of aviation soot and sulphate aerosols on lower-altitude cloud characteristics. Recent studies (e.g. Gettleman and Chen 2013, Righi *et al* 2016, Kapadia *et al* 2016) indicate that these effects may be substantial, but also that there are large uncertainties in their quantification. We have enough information and knowledge about major atmospheric processes to start the implementation and demonstration in an operational environment. Once the uncertainties in the other non-CO_2 components are reduced, they could be incorporated within the same methodological framework as that presented here.

The different timescales of the impacts of CO_2 and contrails makes the comparison dependent on the chosen time horizon in the CCF (Fuglestvedt *et al* 2010). Here we defined a metric, reflecting a mean temperature change within a short time scale (20 yr) for implementing the climate-optimized routing on a daily basis. The results do not vary strongly for longer time horizons (100 yr). Different emission assumptions, especially pulse emissions, might have a strong impact on the results, since they affect the weighting between short-term, such as the less certain contrail effects, and long-term effects, such as the more certain CO_2 impacts. However, emission assumptions such as pulse emissions are not focusing on assessing the climate impact of a strategy change and hence are not appropriate to analyze our operational climate-optimized routing strategy.

There are open questions in ATM research and the financial and political framework. For example, what implications does climate-optimized routing have on ATM, e.g. the controller's work load? Which market-based measures are required? What kind of metric and what time horizon is most relevant for a pursuit climate target? How should the bookkeeping be performed for the individual contributions to climate change from non-CO_2 emissions?

In our approach, the routes which reduce the climate impact avoid regions where warming contrails are formed or the ozone impact is large. However, routes are also favored, where contrails contribute to cooling or the emission of NO_x leads to a methane reduction which cools more than the increase in ozone warms. This raises the question, to what extent should additional contrail formation be allowed, which—over a chosen time span—cools the global climate more than the additional CO_2 emitted by climate optimized-routing warms. These questions have to be considered carefully for any climate-optimized routing. In the light of increasing air traffic and the goal of climate policy to stabilize climate change below 2 °C, there is the need to mitigate aviation's climate impact. The approach and road map introduced here may allow a large reduction in aviation's climate impact in 20 yr' time using the current aviation system and can be complemented by advances in air frame and engine design.

4.2. Comparison to previous work

The idea of avoiding climate sensitive regions was formulated previously (Sausen *et al* 1994, Mannstein *et al* 2005), but until now previous studies have only considered a trade-off between fuel consumption and contrails for a limited air traffic sample rather than the detailed analysis of all major aviation climate impacts for a complex air traffic sample presented here. Sridhar *et al* (2010) investigated the air traffic in the United States on 1 August 2007 and found that 53% of the contrails could have been avoided with an increase in fuel consumption of around 3%. For a more eco-efficient situation they found a reduction in contrail formation of 35% and a cost increase of 0.23%. In another study Sridhar *et al* (2011) analyzed the 24 May 2007 and flights between 12 city pairs and found that the time spent in contrail forming regions can be reduced by more than 70% associated with an increase in costs of 2%. Hartjes *et al* (2016) investigated fuel cost changes when optimizing a flight from Amsterdam to Washington DC and found an increase in costs of 1% for avoiding contrails formation. Schumann *et al* (2011) investigated the global fleet on the 6 June 2006 and calculated integrated radiation changes from contrails and CO_2 and found that by vertical shifts of individual flights the radiation changes can be reduced by 97% at an increase of costs of 0.2%. These results cannot directly be compared to our findings. However, they show the same tendency, i.e. small changes in routings and costs in the order of less than 0.5% potentially lead to a substantial reduction in the impact on climate.

5. Summary

We have adopted a detailed modelling framework to estimate the benefits and costs of air traffic routing options over the North Atlantic. The results for 5 representative winter and 3 representative summer situations clearly indicate the large potential to reduce the climate impact of aviation by roughly 10% at relatively low costs of 1%. In all weather situations, routings could be found which reduce the climate impact at low costs, though the intensity in climate impact reduction varies. Although cost increases are low, they probably constitute a barrier to implementation since the airline's return on investment is also in this order of magnitude. However, with a market-based measure in place, costs for climate-optimized routing could be traded with costs for equivalent CO_2 emissions and climate-optimal routing would become beneficial for both climate and airlines.

The concept of climate-optimal routing is not mature enough to be directly implemented in the real world basically for 4 reasons. First, the calculation of the climate-change functions must be robust and fast enough to become operational. Second, consensus should be achieved on how to deal with cooling effects, i.e. to what extent should additional contrail formation be allowed, which—over a chosen time span—cools the global climate more than the additional CO_2 emitted by climate-optimized routing warms. Third, the implications on ATM have to be identified. Although safety issues are not limiting the results for the North Atlantic flight corridor they might limit the applicability in areas of higher air traffic densities. And finally, a market-based measure or alternative measures are required to foster climate-optimal routing. Our study clearly shows the benefits in climate impact reduction, if these barriers can be overcome.

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